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TECHNICAL NOTE

No. 965

THE EFFECT OF TEMPERATURE ON SHEET METALS FOR AIRPLANE FIREWALLS

By Willard Mutchler

National Bureau of Standards



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SUMMARY

Tests were conducted on 5 uncoated steels and on 20 steels with various coatings to determine the effect of temperature on the tensile properties and surface characteristics of the metals. The metals were subjected to furnace-heating tests over a range of temperatures from 1000° F to 2000° F for 2½, 5, 15, and 60 minutes and to flame-impingement and airplane-fire tests. The surface oxides formed at different temperatures were noted and the tensile strength and ductility of the metals determined for the various temperatures and periods of heating. The tests showed the following results:

1. In general, all materials investigated were capable of withstanding exposure to temperatures not exceeding 1700° F for periods up to 15 minutes without a serious deterioration in tensile properties.
2. Stainless steel proved to be the best of the uncoated materials tested; low carbon steels containing 1 percent silicon were better than steels without silicon.
3. Stainless-clad plain carbon steel exhibited very little change in properties over the most severe heating conditions.
4. Chromium-nickel-alloy coatings and aluminum coatings on plain carbon steel sheets proved to be more resistant to high temperatures for periods of exposure up to 60 minutes than did coatings of zinc or of zinc over nickel.

INTRODUCTION

As a result of the shortage of critical materials, such as steel alloys containing nickel, an investigation was conducted by the National Bureau of Standards with cooperation from the Civil Aeronautics Administration to find satisfactory materials to replace

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these alloys, which are currently being used in airplane firewalls. This work was requested by the National Advisory Committee for Aeronautics.

This report covers the results of furnace-heating, flame-impingement, and airplane-fire tests that were conducted on 5 uncoated steels and on 20 steels with coatings to determine the effect of temperature on the tensile characteristics of the materials. Charts are presented to show the changes in tensile properties with temperature and time of heating; photographs showing the changes in surface and in microstructure are also presented.

The author wishes to express his appreciation and thanks to George L. Pigman, aided by Paul E. Anderson of the CAA, who conducted the airplane-fire tests, together with Philip S. Klebanoff and Paul S. Ballif of the National Bureau of Standards. Much of the work on heat treating and preparing the metallographic samples and photographs was done by William G. Galvin, Miss Hildreth O. Griffin, Mrs. Ernestine M. Turner, Mrs. Marion E. Barber, and Miss Margaret S. Corry, all of the Division of Metallurgy of the National Bureau of Standards.

MATERIALS

The sheet metals (table 1) tested were (1) plain carbon and alloy steels without surface coatings and (2) low carbon steels with protective coatings. The relative merits of the various coatings might have been determined more accurately had it been possible to use sheets of uniform chemical and physical characteristics. Such a uniformity, however, was impracticable inasmuch as the sets submitted by one manufacturer varied considerably from those of another, particularly in tensile properties.

The uncoated metals used were (1) very low carbon steels, (2) a steel containing approximately 1 percent silicon, (3) a low alloy steel containing approximately 5 percent chromium and 0.5 percent molybdenum, and (4) a stainless steel with approximately 20 percent chromium and 10 percent nickel (18-8 type).

The surface coatings consisted of (1) zinc or zinc on nickel applied by electroplating, (2) aluminum applied by hot dipping and by metal spraying, (3) chromium-nickel alloy applied by metal spraying, and (4) a stainless steel with 18 percent chromium and 9 percent nickel applied by the cladding process.

The photomicrographs (fig. 1) of each material in the "as received" condition reveal the variations in the extent of alloying and in the thickness (table 1) of the surface coatings. The coatings rank as follows in decreasing order of thickness: chromium-nickel alloys, metal-sprayed aluminum, stainless-clad, hot-dipped aluminum and zinc, zinc on nickel. Owing to the differences in the thickness of the coatings and their relatively slight influence on the tensile properties (table 1), the tensile strengths plotted on the curves in this paper are based upon the areas of the unalloyed section of the original basis metal.

TESTING PROCEDURE

Samples of each material, in the form of standard A.S.T.M. sheet tensile bars with 1/2-inch reduced sections, were heated in an electric furnace under ordinary atmospheric conditions at temperatures of 1000°, 1100°, 1200°, 1300°, 1400°, 1500°, 1600°, 1700°, 1800°, 1900°, and 2000° F for periods of 2½, 5, 15, and 60 minutes, with a few exceptions as noted later. After removal from the furnace they were cooled in air and the strength and ductility were determined by tensile tests.

Smaller specimens, each 1-inch square, were heated by means of an impinging flame at the same temperatures and for the same periods as those heated in the furnace, except that heatings at 1700° F and 1900° F were omitted.

Panels 9 by 12 inches were subjected to actual airplane-fire tests in a unit consisting of the engine nacelle and related structure of an airplane (fig. 2, reference 1). The fires were started in the engine and were usually extinguished within 30 seconds. The test panels were inserted in the nacelle wall, approximately 2 feet behind the firewall (fig. 2). Tests had demonstrated that at this location the temperature of the fire corresponded closely to that attained on the firewall. Each panel was exposed to several fires and the maximum temperatures were recorded. Changes in properties were determined on standard tensile bars cut from the panels after the fire tests.

Macroscopic and microscopic examinations were made on all specimens; the surface appearance and the microstructure resulting from the furnace heating were recorded photographically and the change in tensile properties was determined. (See figs. 3 to 23.). The microscopic examinations were made on samples cut from the grip (unstressed) ends of the tested tensile bars. The surface appearance

of the representative panels after the airplane-fire tests is shown in figure 24. Figure 25 is a summary chart showing the changes in tensile properties after furnace heating of the metals investigated.

RESULTS

Metals without Surface Coatings

Low carbon steels. - Sheets 1a and 1b (table 1) were from the same lot and were of equal thickness, but sheet 1b was stiffened by a "design-strengthened" wavy-line pattern (fig. 3) that had been stamped into the sheet. The pattern consisted of a series of alternate wave troughs and crests and the sheet had an over-all thickness of 0.043 inch when measured on adjacent crests. Sheet 1c was from a different lot, was somewhat thicker, and had been sandblasted on one side. The effect of the working on sheets 1b and 1c was reflected in their higher strength and lower ductility.

These three steels were heated in the furnace for only the 5- and the 60-minute periods. The resulting changes in surface appearance (figs. 3 and 11) were associated with progressive oxidation, accompanied by a decrease in thickness, with increase in temperature and time of heating. The oxide coatings formed more rapidly and were correspondingly thicker, for a specific heating condition, than on the other uncoated metals.

The changes in tensile properties on sheets 1a and 1b were markedly similar and are plotted in figure 4 so that the range in properties is indicated by the ordinates on the continuous lines. The pattern caused no improvement in the tensile properties when the steels were heated but did not prove detrimental. At 1000° F to 1300° F the changes are indicative of an annealing effect, particularly on the initially stronger sheets 1b and 1c. Above 1400° F at the 60-minute heating period, there occurred a rapid loss in tensile properties. At 1900° F and 2000° F oxidation was severe. This oxidation rendered the material so brittle that the specimens broke during handling while being removed from the furnace. The effect of the greater thickness of sheet 1c is manifested in its retention of higher tensile properties, particularly under the most severe heating conditions.

The photomicrographs (fig. 5) of samples heated in the furnace reveal that the principal changes in microstructure were related to grain growth. Larger grain sizes were attained on sheets 1b and 1c, which initially were more work-hardened than sheet 1a. At the lower temperatures and shorter heating periods, the microstructures of

specimens subjected to a flame corresponded closely to those heated in the furnace. At and above 1800° F for the 2½-minute heating, and similarly at 1500° F for the longer heating, pseudo-martensitic and acicular structures (fig. 6) appeared on regions nearest the flame. These structures may have been the result of "burning" and, inasmuch as the thermocouples were attached to the side away from the flame, the recorded temperatures were somewhat lower than the maximums. The oxide films that formed on the heated specimens were frequently of complex structure (fig. 6) and usually consisted of several distinct layers.

No fire tests in the airplane assembly were made on these steels. It is noteworthy, however, that a relatively thick firewall in the airplane assembly, consisting of 0.040 inch of ordinary black iron, functioned satisfactorily throughout 800 fires, each of approximately 30 seconds' duration (reference 1).

Low alloy steel containing silicon. - Sheet 2 (table 1) contained approximately 1 percent silicon and less than 0.05 percent carbon and was approximately half as thick as the low carbon steels previously discussed.

The steel containing silicon had greater resistance to oxidation (figs. 3 and 11) and, although the changes in surface appearance resembled the changes that occurred on the plain carbon steels, the oxide films were thinner. Specimens heated for 60 minutes at 1900° F and 2000° F broke in handling after cooling.

Duplicate specimens of 1-percent silicon steel were heated for 2½, 5, 15, and 60 minutes in the electric furnace. The samples heated for 2½ and 5 minutes at 1300° F to 1500° F and at 1700° F to 1900° F exhibited air-hardening effects (fig. 7), but there was no serious loss in tensile properties. At the longer heating periods these air-hardening effects were suppressed at 1300° F to 1400° F, whereas above 1600° F a loss in tensile properties occurred at a somewhat less rapid rate than on the plain carbon steels. Changes in microstructure were characterized by grain growths (fig. 5) and the solution and precipitation of minor constituents. No flame impingement or airplane-fire tests were made on this material.

Low alloy steels containing chromium and molybdenum. - Sheets 3, 4a, and 4b (table 1) contained approximately 5 percent chromium and 0.5 percent molybdenum. Sheet 3 contained 0.02 percent carbon and sheets 4a and 4b contained 0.10 percent carbon. Sheet 4b was approximately 30 percent thicker than the others.

The surface oxidation on these steels (figs. 8 and 11) resembled the oxidation that had occurred on the steel containing silicon but was somewhat less severe. The most marked change upon heating (fig. 9) was the hardening caused by air cooling. At temperatures above 1400° F or 1500° F, even for the short heating periods, the tensile strength approximately doubled but the ductility was greatly impaired. The opinion was advanced that a substitution of 0.5 percent of titanium for the molybdenum would suppress this phenomenon, but the manufacturers were unable to supply such an alloy for investigation.

The alloy containing the higher carbon (sheet 4) possessed greater strength, but the rate of change in tensile properties was markedly similar to that of sheet 3.

Acicular structures (fig. 10) were characteristic of the samples that air-hardened, whereas changes in structure were identical on specimens heated by the flame or in the furnace.

Panels of the chromium-molybdenum steels that were subjected to airplane-fire tests (table 2; fig. 24) also air-hardened and exhibited acicular structures.

Stainless steel. - Sheet 5 (table 1) was a polished, nonstabilized, cold-rolled sheet containing 19.99 percent chromium, 9.82 percent nickel, and 0.09 percent carbon.

The surface appearance of the samples differed in no essential respect from those of the stainless-clad specimens (figs. 6, 8, and 11). Furnace heatings made for 5 and 60 minutes only annealed the metal markedly (fig. 4) with consequent decrease in strength and increase in ductility. Tensile properties remained excellent after the severest heating condition, namely, 2000° F. for 60 minutes. A panel subjected to airplane-fire tests (table 2; fig. 24) reached a maximum of 1500° F. and after heating had an average tensile strength of 146,000 pounds per square inch and an elongation of 13 percent.

Summary of surface changes. - Charts summarizing the changes in surface appearance after heating of the metals without coatings are presented in figure 11 together with a description of the oxides formed on the steels during heating. In general, the described effects in each area of the chart outlined were more severe as the temperature and time of heating increased.

Low Carbon Steels with Surface Coatings

Stainless-clad. - Sheets S1 and S2 (table 1) consisted of two different thicknesses of a low carbon steel clad on both sides with layers of stainless steel constituting 17 to 19 percent of the total thickness. The coating contained 17.95 percent chromium, 9.15 percent nickel, and 0.05 percent carbon.

The surface appearance of specimens heated for the shorter periods at the lower temperatures (figs. 8 and 11) indicated the formation of thin oxides that yielded interference colors of brown, dark blue, and purple. At higher temperatures and longer heating periods, gray-black oxides formed, but these were much thinner than on the uncoated low alloy and plain carbon steels.

The tensile properties (fig. 7) of the stainless-clad steels were practically unaffected when samples were heated for $2\frac{1}{2}$ and 5 minutes from 1000° F to 2000° F. Although losses resulted when the samples were heated for the longer periods, excellent tensile properties were retained after heating at 2000° F for 60 minutes.

The microstructures (figs. 6 and 12) of the specimens heated in the furnace and by the flame were very similar. The grain boundaries of the stainless coatings nearest the flame, however, were wider, particularly for the more severe heating conditions. Specimens heated by flame at and above 1800° F for 60 minutes exhibited acicular structures on the areas adjacent to the flame.

Two panels each of sheets S1 and S2 were subjected to the airplane-fire tests (table 2; fig. 24) and retained excellent physical properties.

Chromium-nickel alloy coatings. - These metal-sprayed coatings on sheets f1 and f2 (table 1) were applied on only one side to SAE 1010 sheets of greater thickness (0.031 in.) than was used for any of the other coatings investigated. A sealing agent was stated to have been sprayed on the coating of both sheets and sheet f1 had a layer of sprayed aluminum between the sealing agent and the chromium-nickel alloy. These coatings were much thicker than any of the others tested. A "greasy" aluminum-colored stain on the fingers resulted on handling.

Changes in surface appearance (figs. 13 and 23) on heating were confined to slight discolorations, dulling, and oxidation of the uncoated surfaces; the greasy feeling and staining of the fingers on handling disappeared. Part of the losses in tensile

properties (fig. 14) were due to oxidation on uncoated surfaces and part to the annealing. There was some evidence of an alloying reaction at 1400° F on samples heated for 60 minutes.

Microscopic examinations of specimens subjected to an impinging flame revealed the development of acicular structures on the basis metal nearest the flame on samples heated above 1700° F for 15 minutes, or above 1500° F for 60 minutes. Although somewhat reduced in thickness, the coatings remained intact and adherent at the most severe heating conditions attained in the furnace (fig. 15) or by flame and no iron oxide scale formed on the coated surface.

Aluminum coatings applied by hot dipping. - Sheets a, b, c, d (table 1) were SAE 1020 steels that had been coated on both sides with aluminum (0.0015 to 0.0020 in. thick) by a hot-dipping process. The manufacturer stated that, aside from variations in surface finish, there were no essential differences in the properties of the coatings. The coatings on sheets a and c appeared similar, were of equal thickness, and had a uniform polished finish much resembling that on ordinary rolled aluminum sheet, but both the over-all thickness and the tensile strength were greater for sheet c. The coating on sheet b was less highly polished and was patterned uniformly with areas of a matte finish, whereas that on sheet d exhibited equiaxed grains, each approximately $1/8$ inch in diameter. Sheet d was the thinnest and was stated to be experimental in order to establish the minimum gage tolerance for the basis metal.

The changes in surface appearance (figs. 16 and 23) caused by heating were chiefly related to partial melting of the outer surface of the coating and to alloying reactions between the coating and the basis metal. Iron oxides were not formed on the surface even under the most severe conditions of heating in the furnace. In the flame-impingement tests, however, the coatings were occasionally burned through at small areas where the flame impinged at 1800° F and above for the $2\frac{1}{2}$ - and 5-minute heatings and at 1600° F and above for the longer periods. In these instances, iron oxides were formed in the cavities. (See fig. 6.)

Changes in tensile properties of all these materials were confined to a limited range defined by the ordinates on the continuous lines of figure 17. The initial annealing effect on sheets c and d quickly brought their properties within this range, usually at temperatures below 1400° F. Sheet d suffered serious loss in ductility when heated above 1600° F for 15 minutes but exhibited gains in tensile strength.

Evidences of alloying action (fig. 18) between the basis metal and the coating became more pronounced as the severity of the heating conditions increased. Above 1800° F for the 15- and 60-minute heatings the alloying was advanced and ultimately almost none of the original basis metal remained unalloyed. This final alloy as it increased in depth was therefore responsible for the increase in strength already noted.

Aluminum coatings applied by metal spraying. - Sheets e1 and e2 were very low carbon steels of different thicknesses on which coatings had been applied, on only one side, by metal spraying. The manufacturer stated that a varnish-type sealing agent was applied to the sprayed coating, following which the material was wire-brushed and heated at 1450° F to promote alloying.

The surface changes (figs. 16 and 23) produced on heating this coating were confined almost entirely to variations in color and no iron scale was visible on the coated surface. The interference colors resulted from the diffusion of iron through the aluminum and ranged from gray-brown, to brilliant purple, to lighter blues. A striking purple color occurred at 1800°, 1700°, 1600°, and 1400° F as specimens were heated for 2½, 5, 15, and 60 minutes, respectively.

The tensile properties (fig. 14) were lower on specimens heated above 1600° F for 15 minutes and above 1400° F for 60 minutes, undoubtedly because of oxidation of the uncoated surfaces. The extra thickness of sheet e2 was reflected in its lower rate of loss of strength and ductility.

In general, the changes in microstructure (fig. 16) were similar to the changes that occurred on the steels coated with aluminum by hot dipping. At the higher temperatures and for the longer heating periods, the aluminum-iron alloy increased greatly in depth. On specimens heated at 2000° F for 60 minutes the end product consisted almost entirely of this alloy. In the flame-impingement tests no burning through, such as occurred on the hot-dipped aluminum, was found.

Single panels of each of the steels coated with aluminum were subjected to the airplane-fire tests (table 2; fig. 24); the maximum temperature recorded was 1100° F. A slight annealing occurred on the steels of stiffer temper, but no deleterious effects were noted.

Zinc coatings. - Sheets A to G (table 1) consisted of thin sheets of SAE 1010 steel which had different "corrionized" coatings. These coatings consisted of thin electrodeposits, zinc over nickel,

whose total thickness on one side ranged from 0.0002 to 0.0005 inch. The manufacturer stated that sheets A to D had been heated to promote alloying by diffusion, while sheets E to G had not been heated after being coated. The coating on sheet G had also been applied on sheets of heavier gage (sheets G1 and G2, table 1). The ratios of nickel to zinc were approximately 1:1 on sheets B, C, D, and F; 1:3 on A and E; and 4:1 on G. Only the coating on sheet B, as received, showed much evidence under the microscope of the diffusion heat treatment and on it two distinct alloying layers were discernible in some areas (fig. 1) on the nickel. The ratio of nickel to zinc was not uniform on sheet B and was 3:1 at some locations.

Electrodeposited coatings of zinc alone, approximately 0.002 inch thick, had been applied on sheet H (table 1). The basis metal consisted of at least two lots of steels (fig. 22) of the SAE 1010 and SAE 1020 types.

The zinc coatings were more chemically reactive, at elevated temperatures, than any of the others. The surface reaction products consisted of varicolored, loosely adherent, blistered, powdery oxides of zinc (figs. 13, 19, and 23) some of which were lost in handling prior to photographing. On sheet H, which was electroplated with zinc alone, the coating burst into flame when removed from the furnace at 1700° F and above. At higher temperatures, particularly for the longer heating periods, the surface became coated with a thick scale consisting largely of black iron oxide.

Differences in the surface appearance for the A, B, C, and D group were slight, as was the case, in general, for the coatings on sheets E, F, and G, although the sheet G samples were usually the least affected by the heating. There were, however, marked differences in the surface appearance of the coatings of the two groups.

The results of the tensile tests (fig. 20) on the corrosioned metals indicated that the first effect of heating was to anneal the steel. The rate of change in tensile properties on heating was very similar for the two classes of coatings. The E, F, and G group, particularly the G, exhibited a lower rate of loss under the most severe heating conditions, perhaps owing to the initially greater thickness of these coatings. In general, the corrosioned steels withstood heating to 2000° F for 5 minutes and to 1700° F for 15 minutes without marked lowering of the tensile properties. A heating period of 60 minutes resulted in a marked deterioration above 1400° F and the properties of the sheet were not much better than those of uncoated steels heated under the same conditions.

Only remnants of the powdery surface coatings could be retained on samples mounted for microscopic examination (figs. 15 and 21), but these were sufficient to reveal their lack of adherence. In general, an increase in thickness of the alloying layers of zinc with iron was noted as the severity of the heating conditions increased and thick layers of iron oxide ultimately formed. Samples heated in the furnace and by the flame yielded similar microstructures, but at areas where the flame impinged the coatings were burned through at 1500° F and above; acicular structures characterized the basis metal (fig. 6) and iron oxides formed in the cavities.

Several panels (table 2) from sheets of this group were subjected to the airplane-fire tests and the results were very similar to those obtained on samples heated in the electric furnace. These panels were the thinnest tested and warping was most pronounced of all (fig. 24).

Summary of surface changes. - Charts summarizing the changes in surface appearance after heating of the steels having surface coatings are given in figure 23. In general, the described effects in each area of the chart outlined were more severe as the temperature and time of heating increased.

DISCUSSION OF COMPARATIVE BEHAVIORS

In order to permit more direct evaluations of the relative merits of the materials investigated, the results were collectively summarized (fig. 25). Average values of the tensile tests, both for the two shorter and the two longer heating periods, were calculated (1) for alloys of similar chemical compositions and (2) for typical and similar surface coatings applied to the low carbon steels. Percentages were calculated on the basis of the average properties of all the uncoated samples, whether or not they were heated; the same procedure was followed for the coated steels.

Steels without Surface Coatings

The changes in surface appearance that resulted on heating the uncoated steels were closely related to their susceptibility to oxidation. Oxide scales formed in greatest quantity on the plain carbon steels and were much less prevalent on steels containing 1 percent silicon, or 5 percent chromium, in that order. The thin films formed on the stainless-steel samples gave interference colors, but thin scale formed at the higher temperatures and the longer heating periods.

Plain carbon steels, for the shorter heating periods, gradually decreased in tensile strength and elongation, owing to the combined effects of annealing and oxidation. The rate of loss was a function of the initial thickness of the material, being lower for the thicker sheet. For sheets 0.023 inch thick, heating for 5 minutes at 2000° F lowered the strength from an initial 50,000 pounds per square inch to 40,000 pounds per square inch, while the elongation dropped from a value of 32 to 21 percent. These steels showed a rapid rate of loss when heated for longer periods above 1400° F.

Low carbon steels having 1 percent silicon had greater resistance to oxidation than those without silicon. Such sheet, 0.014 inch thick, retained its initial strength and good ductility when heated for short periods and two stages of air hardening occurred. At the longer heating periods, likewise, the retention of strength and ductility was better than for the plain carbon steels.

Low alloy steels containing 5 percent chromium, 0.5 percent molybdenum, and 0.10 or 0.02 percent carbon retained excellent tensile properties up to 1500° F, but thereafter air hardening resulted in high strength but with a serious impairment of ductility without regard to the heating period.

Stainless steel of the 18-8 type initially possessed much higher tensile strength than any of the other alloys investigated. Heating resulted in a pronounced annealing, the rate of which was influenced to only a slight degree by the heating period.

Low Carbon Steels with Surface Coatings

The surface coatings investigated were considered as representing these four types: (1) stainless cladding; (2) chromium-nickel alloy; (3) aluminum; and (4) zinc.

Changes in surface appearance on heating the stainless and the chromium-nickel alloy coatings were related to the formation of very thin oxide films as shown by interference colors and, on prolonged heating, of thin oxide scales. The coatings remained intact and adherent under the most severe heating conditions and appeared to protect adequately the steel basis metal. The aluminum coatings alloyed progressively with the basis metal as the severity of the heating increased, but no iron oxide scale was formed. The coatings applied by metal spraying were less susceptible to marked changes, such as accompanied the partial melting of the hot-dipped aluminum coatings. The zinc coatings were much more chemically reactive with the atmosphere than the other coatings investigated.

Powdery, varicolored oxides, which might be regarded as objectionable, formed at temperatures above 1100° F. Notwithstanding the progressive alloying of the zinc with the basis metal, thick scales of brittle iron oxides were associated with the more severe heating.

The tensile tests revealed (fig. 25) that all the coatings afforded some protection to the basis metal and no serious losses were noted on any of the materials heated for the shorter periods. The superior performance of the stainless-clad steels is apparent. Sheets coated with chromium-nickel alloy or aluminum retained their properties to an acceptable degree except when heated at 2000° F for 60 minutes. It must also be borne in mind that the values given on the diagram for the chromium-nickel alloy and the aluminum include those instances in which these coatings were applied by spraying on only one side of the sheet. Sheets coated with zinc or zinc over nickel were seriously impaired in tensile properties by temperatures above 1600° F when the heating was prolonged.

SUMMARY OF RESULTS

The following results were obtained from macroscopic and microscopic examinations and from tensile tests on the heated samples of the materials tested. The results obtained were much alike regardless of the methods used to heat the samples.

1. In general, all the materials investigated were capable of withstanding exposure to temperatures not exceeding 1700° F for periods up to approximately 15 minutes without serious deterioration in tensile properties. A possible exception was a steel containing 5 percent chromium and 0.5 percent molybdenum, which showed serious impairment of ductility after being heated above 1500° F.

2. Stainless steel proved to be the best of the uncoated alloys investigated inasmuch as the stainless steel retained greater strength and ductility than that possessed initially by most of the other alloys despite a pronounced lowering in properties caused by the annealing action. Low-carbon steels containing 1 percent silicon were superior to those without silicon.

3. Stainless-clad plain carbon steel sheet exhibited very little change in properties under the most severe heating conditions and from that viewpoint may be regarded as somewhat superior in its behavior to ordinary stainless steel sheet.

4. Chromium-nickel alloy coatings and aluminum coatings on plain carbon steel sheets proved to be more resistant to elevated temperatures for periods of exposure up to 60 minutes than did

coatings of zinc or of zinc over nickel. Chromium-nickel alloys and aluminum coatings applied by metal spraying possessed the added advantage of exhibiting less change in surface appearance than the aluminum coatings applied by hot dipping or the electro-deposited zinc coatings.

National Bureau of Standards,
May 1944.

REFERENCE

1. Pigman, George L.: Determination of Means to Safeguard Aircraft from Powerplant Fires in Flight - Part II. Tech. Development Rep. No. 37, CAA, U. S. Dept. Commerce, Oct. 1943.

TABLE 1. - PHYSICAL CHARACTERISTICS AND MECHANICAL PROPERTIES OF THE MATERIALS TESTED IN "AS RECEIVED" CONDITION

Designation (a)	Type of steel	Surface coating	Average thickness				Average initial tensile properties			Composition and treatment
			Side A (in.)	Side B (in.)	Base metal only (in.)	Total over-all (in.)	Tensile strength (lb/sq in.)	Elongation in 2 inches (percent)		
1a	SAE 1010	None			0.0234	0.0235	48,800	48,800	29.0	All steels listed as SAE 1010 were of very low carbon content. Same as 1a, but stiffened with "design-strengthened" No. 5-W Pattern. Overall thickness, 0.043 inch. One surface sandblasted.
1b	do	do			0.0230	0.0230	64,800	64,900	8.0	
1c	do	do			0.0225	0.0225	62,800	62,500	4.8	
2	1 1/2 silicon (Enduro "A")	None			0.014	0.014	51,900	51,900	25.0	Electrical grade.
3	U.S.S.-36-Type 302	None			0.017	0.017	88,800	88,800	9.5	4.6% Cr, 0.54% Ni, 0.00% C. No. 2-D surface finish. 5.00% Cr, 0.52% Ni, 0.10% C. Do.
4a	Enduro 4-6 Cr-Ni	do			0.017	0.017	89,100	89,100	24.6	
4b	do	do			0.022	0.022	76,800	76,800	24.6	
5	U.S.S. 18-8 Type 306	None			0.0175	0.0175	107,900	107,700	8.6	19.00% Cr, 9.22% Ni, 0.00% C.
A	SAE 1010	Electrodeposited zinc on nickel. Corrosion A	0.00018	0.00018	0.010	0.0104	86,600	80,000	14.1	Heated to promote alloying. Nickel, 0.00003 to 0.00006 inch thick; zinc, 0.00013 to 0.00014 inch thick. Heated to promote alloying. Nickel, 0.00009 to 0.00010 inch thick; zinc, 0.00009 to 0.00010 inch thick. Heated to promote alloying. Nickel, 0.00010 to 0.00013 inch thick; zinc, 0.00010 to 0.00014 inch thick. Heated to promote alloying. Nickel, 0.00015 inch thick; zinc, 0.00015 inch thick. Not heated. Nickel, 0.00008 inch thick; zinc, 0.00024 inch thick. Not heated. Nickel, 0.00080 inch thick; zinc, 0.00080 inch thick. Not heated. Nickel, 0.00039 inch thick; zinc, 0.00010 inch thick. Same as steel 1a, but corrosionized. Same as steel 1b, but corrosionized.
B	do	Electrodeposited zinc on nickel. Corrosion B	0.00029	0.00029	0.010	0.0106	61,800	60,300	15.8	
C	do	Electrodeposited zinc on nickel. Corrosion C	0.00025	0.00025	0.010	0.0106	64,700	60,700	15.2	
D	do	Electrodeposited zinc on nickel. Corrosion D	0.00030	0.00030	0.010	0.0106	69,700	69,000	15.2	
E	do	Electrodeposited zinc on nickel. Corrosion E	0.00028	0.00028	0.010	0.0106	67,800	63,600	6.5	
F	do	Electrodeposited zinc on nickel. Corrosion F	0.00040	0.00040	0.010	0.0106	69,200	64,100	7.6	
G	do	Electrodeposited zinc on nickel. Corrosion G	0.00048	0.00048	0.010	0.0110	74,800	67,800	5.1	
G1	do	Electrodeposited zinc on nickel. Corrosion G	0.00050	0.00050	0.025	0.0256	48,900	48,600	29.0	
G2	do	Electrodeposited zinc on nickel. Corrosion G	0.00050	0.00050	0.025	0.0256	64,800	64,800	6.0	
K	SAE 1010, SAE 1020	Electrodeposited zinc.	0.0020	0.0020	0.019	0.023	59,300	49,800	25.0	
a	SAE 1020	Hot-dipped aluminum	0.0015	0.0015	0.014	0.017	66,800	67,800	11.2	Each sample with a different surface finish.
b	do	do	0.0020	0.0020	0.019	0.023	67,300	65,600	11.7	Do.
c	do	do	0.0015	0.0015	0.019	0.022	109,000	95,100	8.5	Do.
d	do	do	0.0020	0.0020	0.011	0.015	61,800	59,800	11.5	Each sample with a different surface finish. An experimental sheet thinner than commercially produced.
e1	SAE 1010	Metal-sprayed aluminum plus sealing agent. Metallize Process No. 11.	0	0.008	0.0156	0.0245	65,000	35,500	24.6	Heated at 1450° F to promote alloying; wire-brushed.
e2	do	do	0	0.008	0.027	0.033	61,600	50,400	16.2	Do.
f1	SAE 1010	Metal-sprayed chromium-nickel alloy plus aluminum and sealing agent. Metallize Process No. 45.	0	0.028	0.051	0.063	66,300	40,900	2.6	Not heated.
f2	do	Metal-sprayed chromium-nickel alloy plus sealing agent. Metallize Process No. 33. (Same as f1 but aluminum omitted.)	0	0.012	0.051	0.043	72,800	56,000	2.6	
g1	SAE 1010	Stainless-steel with U.S.S. 18-8 Type 304. Double Arcarc Fluxsult.	0.0034	0.0038	0.0128	0.0194	108,100	70,000	45.2	Coating contained 17.00% Cr, 9.15% Ni, 0.00% C.
g2	do	do	0.0034	0.0048	0.0168	0.027	108,400	67,500	44.9	Do.

^aThe sheets were furnished by manufacturers as follows: 1a, 1b, G1, G2 by the Rigid-Tax Corp., Pittsburgh, Pa.; 1c, e1, e2, f1, f2 by the Metallizing Engineering Co., Long Island, N. Y.; 2, 4a, 4b by the Republic Steel Corp., Cleveland, Ohio; 3 by the Carnegie-Illinois Steel Corp., Westport, Pa.; 5 by the American Steel & Wire Company, Cleveland, Ohio; A through G by the Standard Steel Spring Co., Coraopolis, Pa.; H by the Glenn L. Warren Co., Baltimore, Md.; a through d by the American Rolling Mill Co., Middletown, Ohio; e1, e2 by the Allegheny-Ludlow Steel Corp., Brackbridge, Pa.

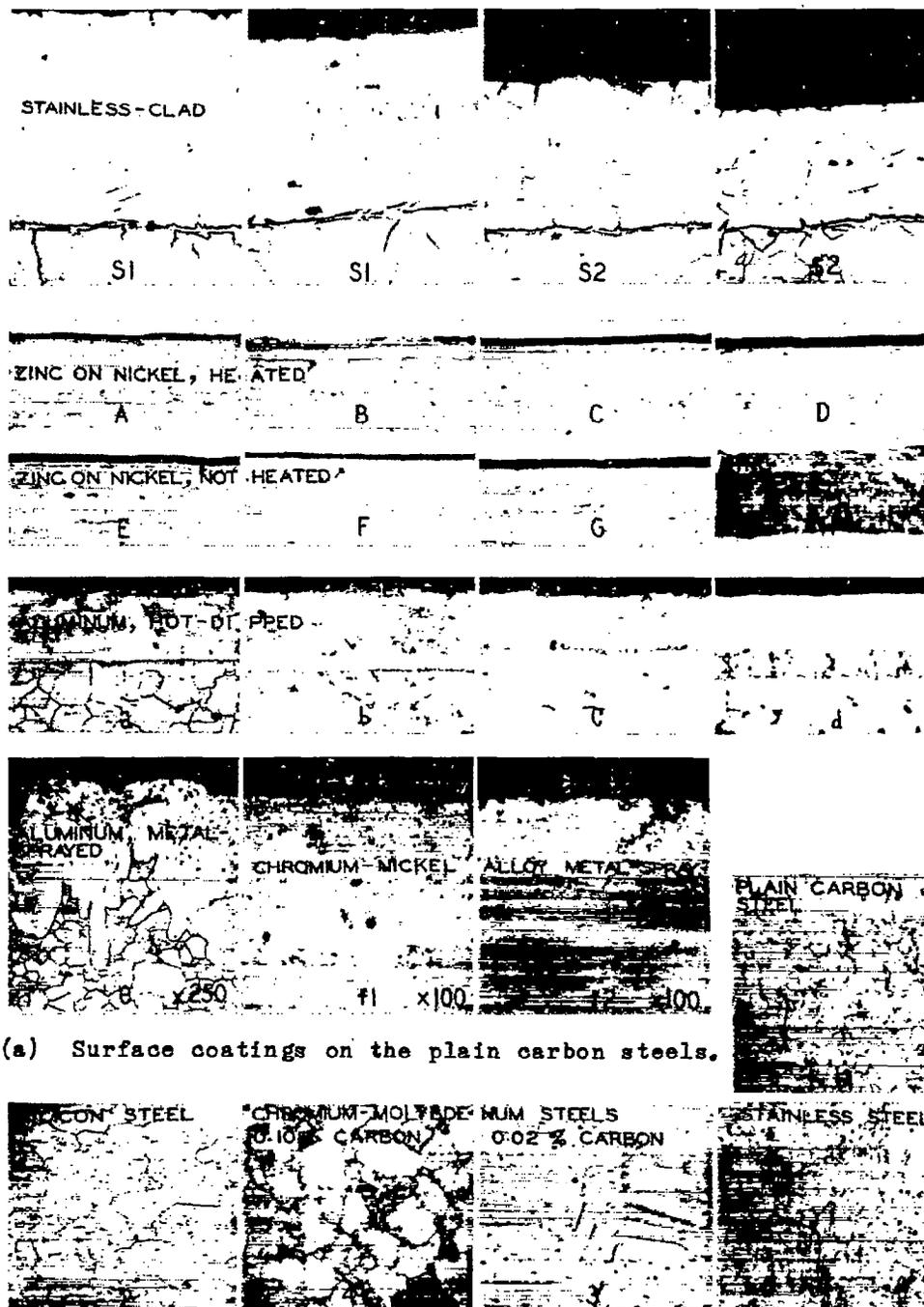
^bValues based upon the thickness of the base metal only.

^cValues based upon the total thickness of the sheet.

TABLE 2
TENSILE PROPERTIES OF THE VARIOUS SHEET MATERIALS
AFTER EXPOSURE TO AIRPLANE FIRE TESTS

Designation	Material	Number of fires	Approximate maximum temperature (°F)	Initial properties		Properties after fire test (a)	
				Tensile strength (lb/sq in.)	Elongation in 2 inches (percent)	Tensile strength (lb/sq in.)	Elongation in 2 inches (percent)
4a	Chromium steel	2	1600	69,100	24.6	139,800	3.7
4b	-----do-----	2	1700	75,800	24.5	148,900	4.4
5	Stainless steel	2	1500	157,700	8.6	146,100	12.8
S1	Stainless-clad	7	1200	105,100	43.2	105,500	39.7
S1	-----do-----	6	1500	105,100	43.2	99,900	38.7
S2	-----do-----	3	1400	108,400	44.9	107,900	44.0
S2	-----do-----	25	1100	108,400	44.9	103,800	44.3
a	Aluminum-coated	5	1100	69,800	11.8	61,800	14.5
b	-----do-----	8	1100	67,300	11.7	62,400	14.4
c	-----do-----	8	1100	109,000	2.3	92,900	5.9
d	-----do-----	6	1000	81,600	11.3	78,100	13.5
e1	-----do-----	9	1100	55,000	24.8	55,100	25.2
A	Zinc-coated over nickel	106	1300	62,500	14.1	52,700	19.5
B	-----do-----	3	1400	61,800	15.8	60,000	22.5
C	-----do-----	3	1400	64,700	15.2	60,100	20.5
D	-----do-----	3	1300	62,700	15.2	62,300	18.1
E	-----do-----	6	1400	67,500	8.5	64,900	24.1
E	-----do-----	9	1400	67,500	8.5	63,200	23.2
F	-----do-----	10	1400	69,200	7.6	64,300	24.9
F	-----do-----	70	1300	69,200	7.6	61,800	24.3
G	-----do-----	148	1400	74,500	5.1	64,500	23.1
G	-----do-----	1	1200	74,500	5.1	62,100	21.1

^aAverage values for 10 to 14 tensile specimens.



(a) Surface coatings on the plain carbon steels.

(b) Microstructure of the steels without surface coatings.

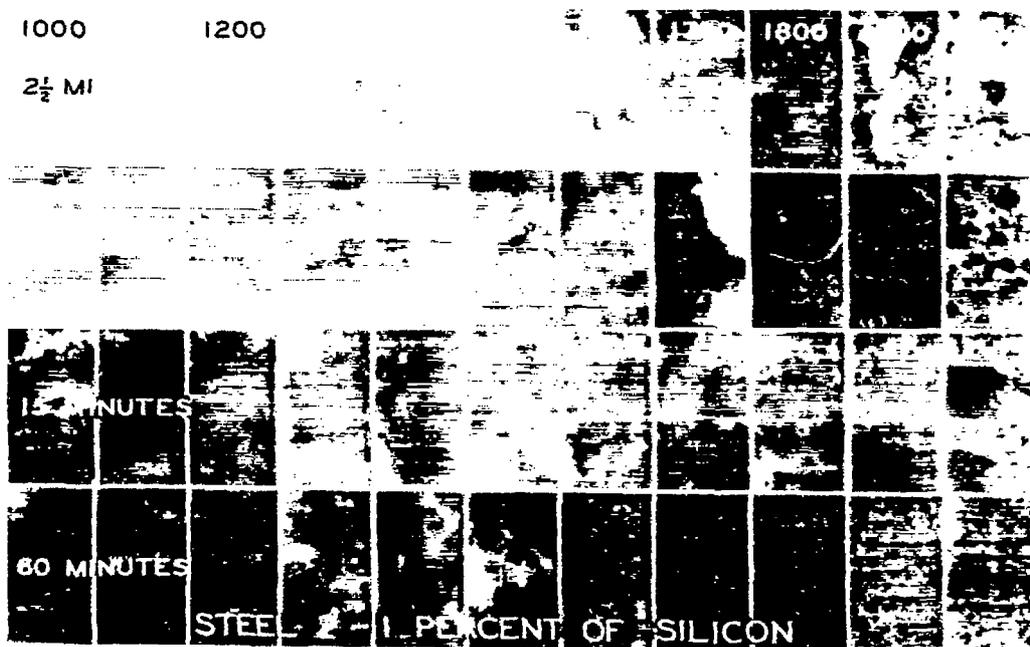
Figure 1. - Cross sections showing the thickness of the surface coatings on the plain carbon steels and the microstructure of the steels without surface coatings. The stainless-clad coatings on each side of the sheet are shown. Originally photographed at X500 (unless otherwise indicated) and reduced to approximately X150.



Figure 2. - Airplane subassembly used in the fire tests showing the location of a test panel in the nacelle skin. XI/12.



(a) Plain carbon steels.



(b) Silicon steel.

Figure 3. - Surface appearance of furnace-heated samples of plain carbon steels (1a and 1b) and silicon steel (2). These steels oxidized progressively as the severity of the heating conditions was increased. Scale formations were thinner on the silicon steel for corresponding conditions of heating. Compare with figure 11. X2/3.

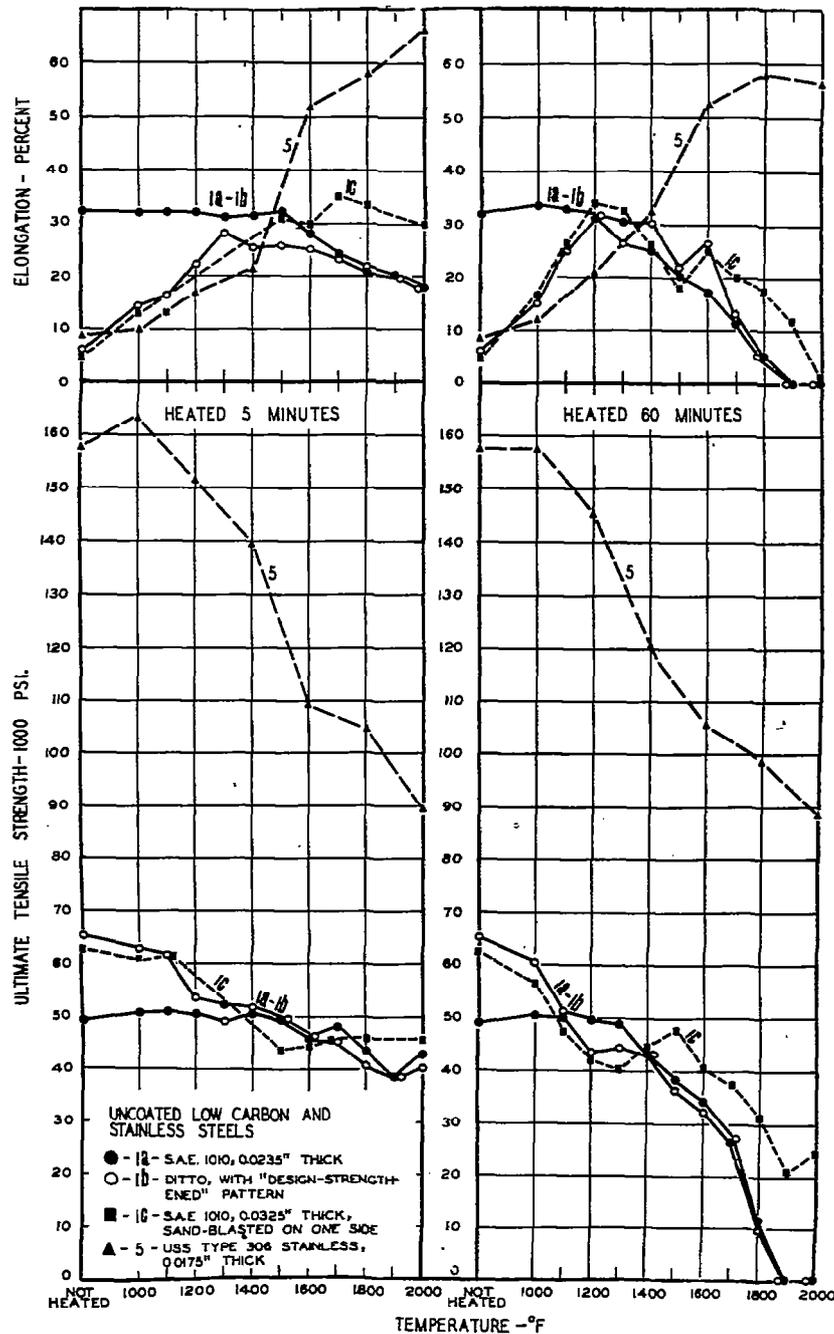
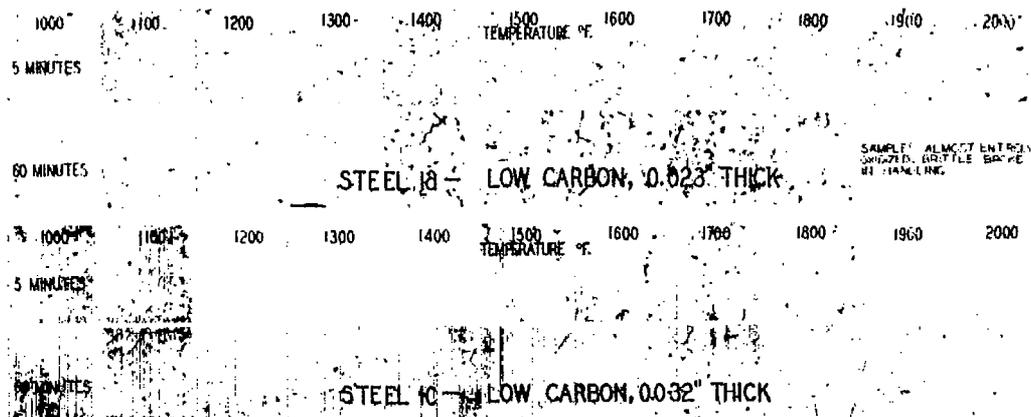
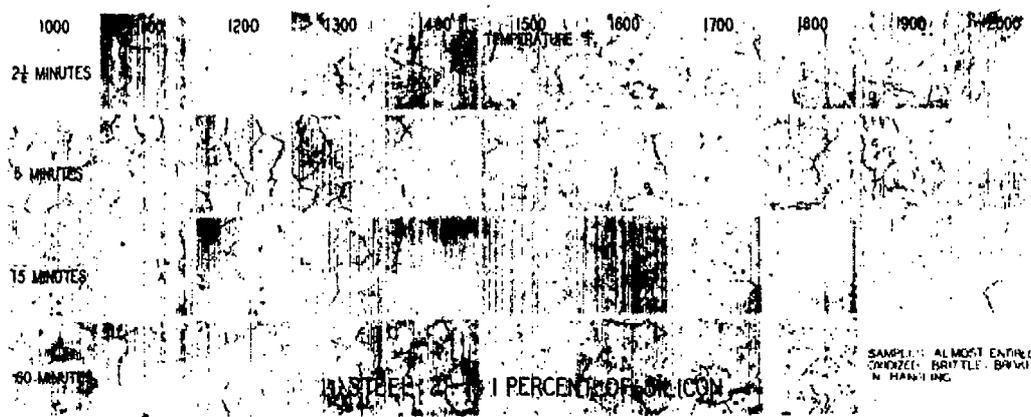


Figure 4. - Changes in tensile properties of plain carbon steels and of stainless steel after furnace heating for 5 and 60 minutes. None of the samples was seriously damaged at the 5-minute heating period. The stainless steel exhibited a more rapid rate of loss in properties than the plain carbon steels but retained higher strength and ductility under the most severe heating conditions. The ordinates of the continuous lines show the range of scatter on one of the low carbon steels.



(a) Plain carbon steels.



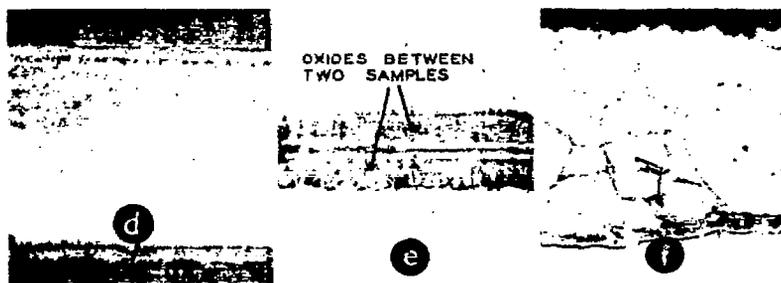
(b) Silicon steels.

Figure 5. - Changes in microstructure of furnace-heated plain carbon steels and silicon steels which were characterized by variations in grain size. Originally photographed at X500 and reduced to approximately X150.

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- (a) Acicular structure of steel 1c after heating at 1800° F for 60 minutes by impinging flame. X125. (b) Acicular structure of steel 1c after heating at 2000° F for 60 minutes by impinging flame. X250. (c) Oxidation at grain boundaries of steel 5 after furnace heating at 1800° F for 60 minutes. X250.



- (d) Entire cross section showing acicular structure of steel D after heating by impinging flame at 1500° F for 60 minutes. X125. (e) Oxide films on steel 1a after furnace heating at 1200° F for 60 minutes. X250. (f) Grain-boundary precipitation of steel S2 after furnace heating at 1800° F for 60 minutes. X250.



- (g) Entire cross section of steel b showing thickness of the aluminum-iron alloy formed after furnace heating at 2000° F for 60 minutes. X125. (h) Steel a heated by impinging flame at 2000° F for 15 minutes showing area where flame burned through the aluminum-iron alloy. X250. (i) Same as (f) at a higher magnification of X500. A chain of smaller constituents, possibly carbides, is precipitated within a second constituent at the grain boundary.

Figure 6. - Microstructure of miscellaneous samples after flame-impingement and furnace-heating tests. All the photographs reduced one half from original magnification.

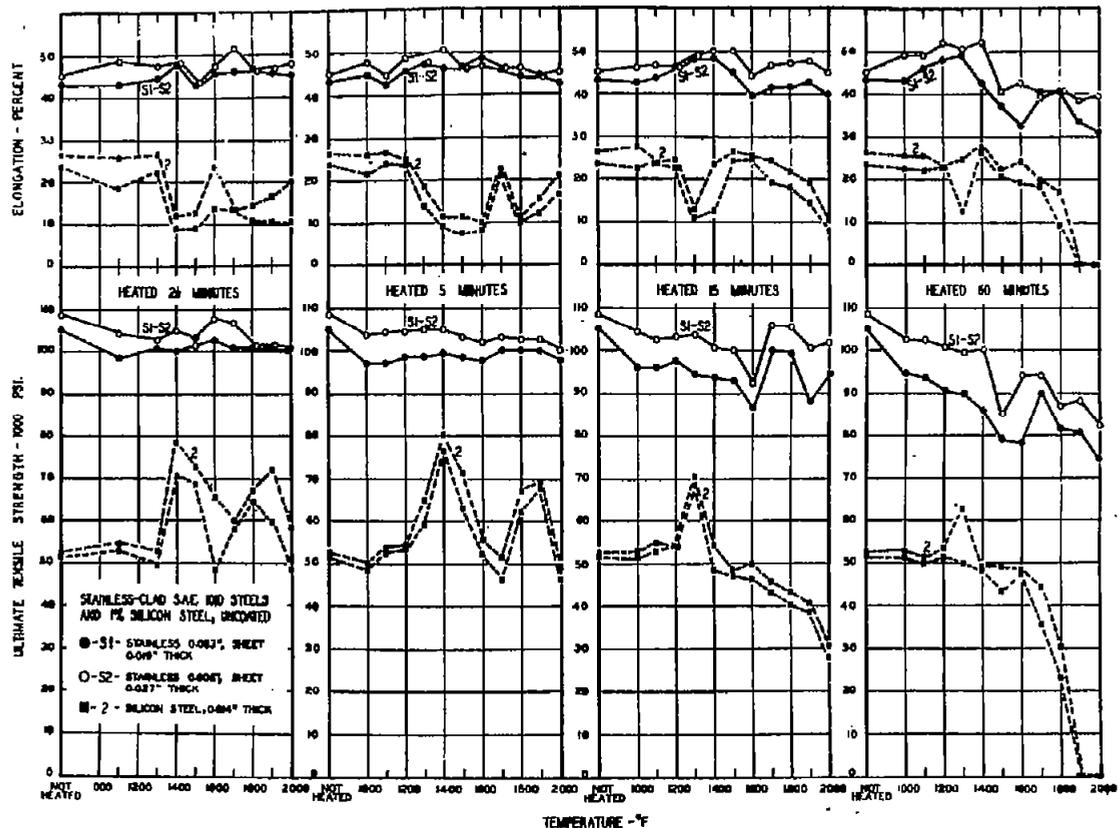
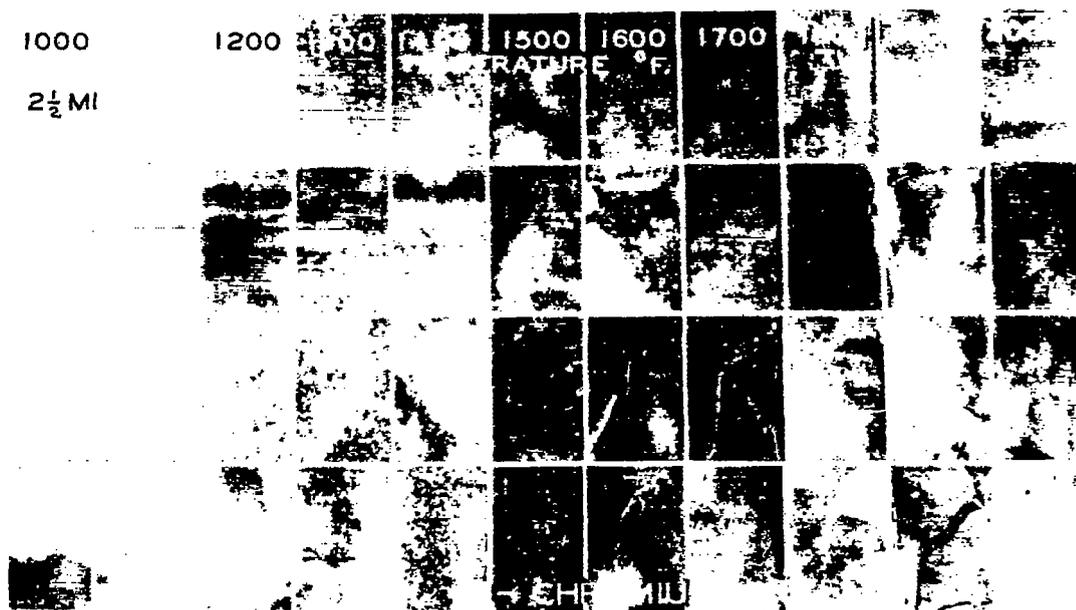


Figure 7. - Changes in tensile properties of furnace-heated silicon steel and stainless-clad steels over various heating periods. Two stages of air hardening, exhibited by the silicon steel at the $2\frac{1}{2}$ and 5-minute heating periods were suppressed or eliminated as the time of heating increased; serious damage occurred only at the most severe heating conditions. The stainless-clad steel suffered less change in properties than any of the other materials investigated.



(a) 5-percent chromium steel.



(b) Stainless-clad steel.

Figure 8. - Surface appearance of furnace-heated samples of a 5 percent chromium steel and a stainless-clad steel. Oxide formations on these steels were thinner than those shown in figure 3 for corresponding heating conditions. The oxides on the stainless steels, except on samples heated at the most severe conditions, were thin enough to produce interference colors. Compare with figure 11. X2/3.

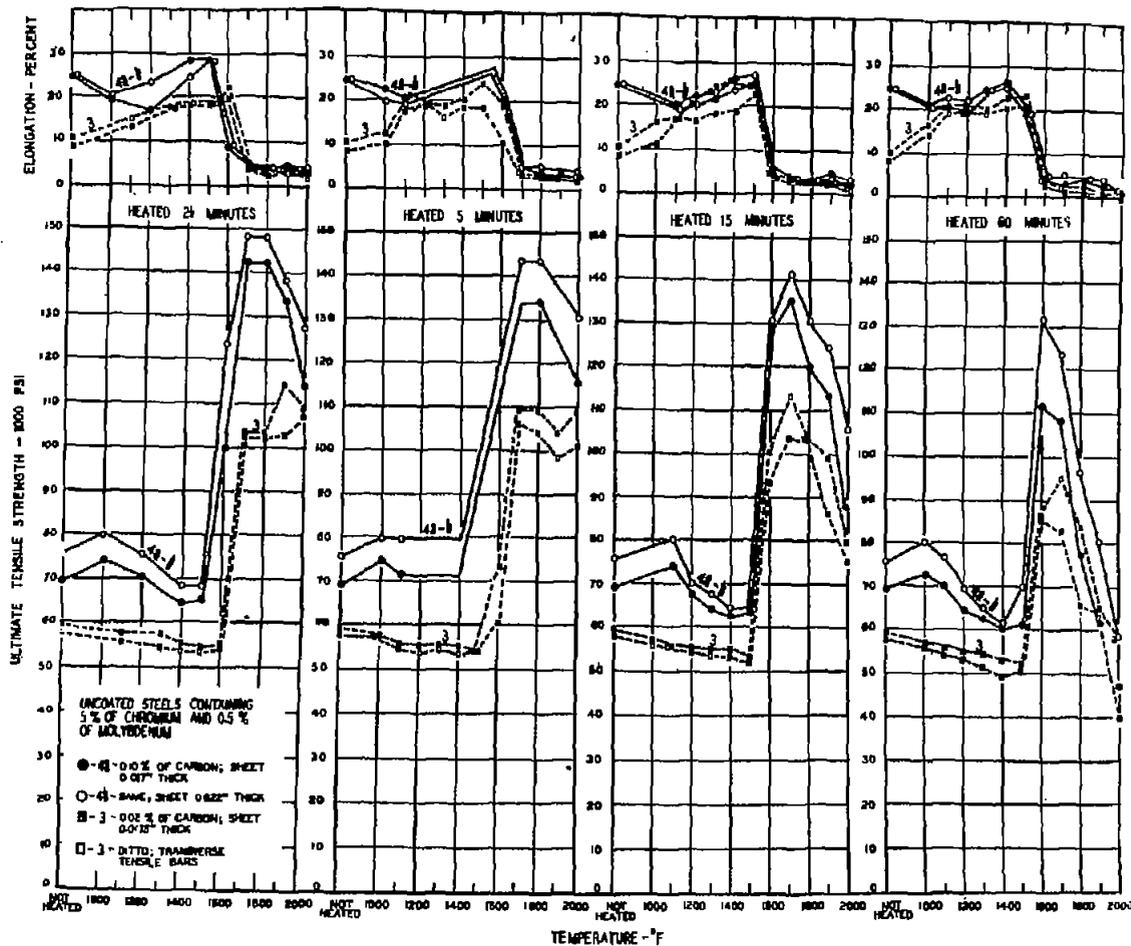


Figure 9. - Changes in tensile properties of furnace-heated steels containing 5 percent chromium. Irrespective of the differences in carbon content of the two steels, air hardening occurred on samples heated above 1500° F and resulted in great increases in strength accompanied by a serious impairment of ductility.

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Figure 10. - Changes in microstructure of furnace-heated steels containing 5 percent chromium were characterized by the acicular structures exhibited by samples which air-hardened at temperatures above 1500° F. Originally photographed at X500 and reduced to X150.

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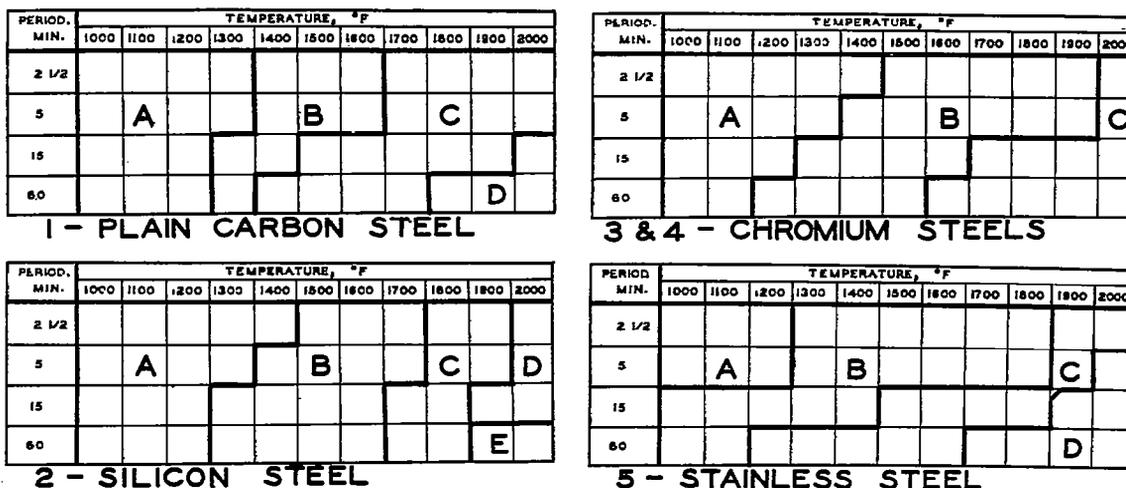
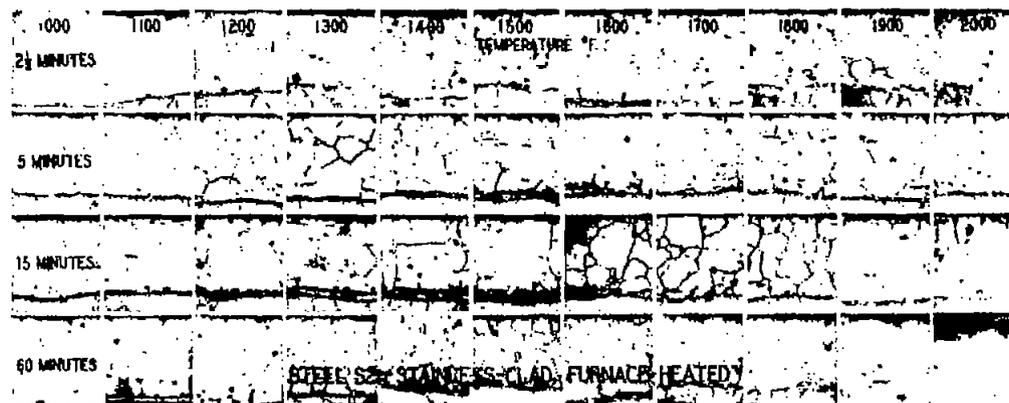


Figure 11. - Summary of changes in surface appearance after furnace heating of the steels without surface coatings. The following table lists the surface oxides formed and their physical characteristics in each area of the charts.

Steels (See table 1.)	Chart area									
	A		B		C		D		E	
	Surface change									
	Oxide color	Characteristics	Oxide color	Characteristics	Oxide color	Characteristics	Oxide color	Characteristics	Oxide color	Characteristics
Plain carbon steels (1a, 1b, 1c). These steels oxidized the worst on heating.	Dark gray with mottled red	Adherent	Gray with red-brown	Loosely adherent; fairly thick	Gray-black	Brittle; loosely adherent; quite thick; somewhat warped	Gray-black	Very brittle; warped; broke in handling		
Silicon steel (2). The oxides formed on these steels were thinner, in general, than on the plain carbon steels.	Dark gray with mottled red	Adherent; not very thick	Light gray over red	Blisters 1/8 to 3/16 inch; loosely adherent; fairly thick	Light gray	Adherent; thick	Gray with thin dark gray beneath	Quite thick; loosely adherent; somewhat warped	Gray with thin dark gray beneath	Much thicker; very brittle; warped; broke in handling
Chrome-molybdenum steels (3, 4a, 4b). Oxidation was less severe than on the silicon steel.	Dark gray and red	Thin; adherent	Red, becoming more completely covered with black	Less adherent	Black	Thick; loosely adherent				
Stainless steel (5, S1, S2). Oxidation was very much less pronounced than on the other steels.	Bright copper interference colors	Thin; adherent	Copper to dark blue interference colors	Thin; dull; adherent	Dull gray to black scale	Thin; adherent	Gray-black	Fairly thick with red rust beneath; less adherent; slightly warped		

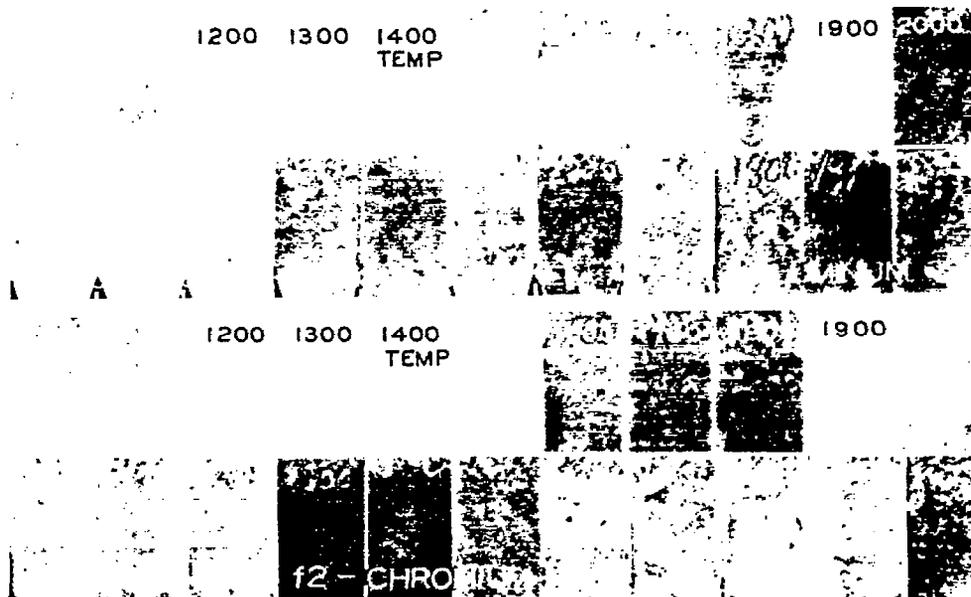


(a) Furnace heated. Originally photographed at X500 and reduced to X125.

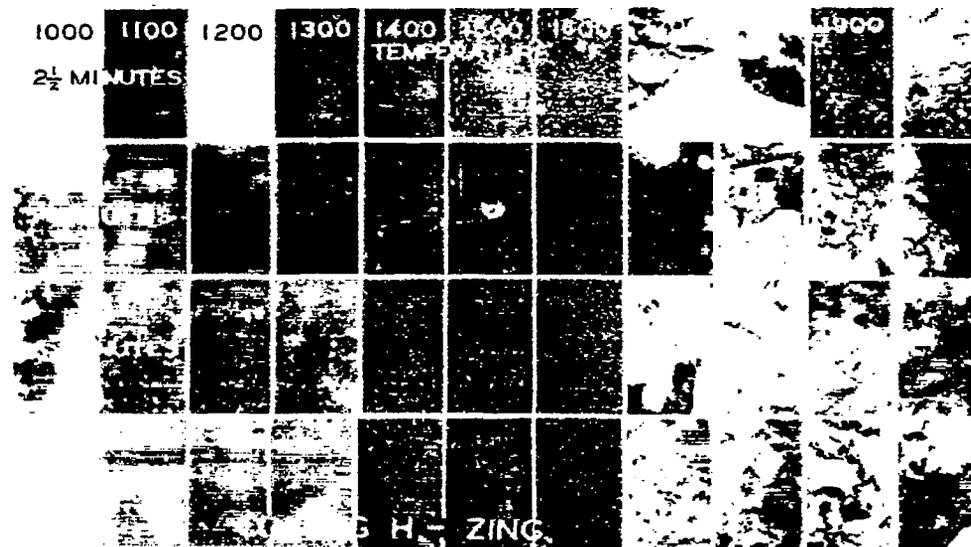


(b) Impinging flame. The surfaces on the right were the ones in contact with the flame. Originally photographed at X100 and reduced to X25.

Figure 12. - The microstructures of stainless-clad steels heated in furnace and by impinging flame. Changes in coating structure were chiefly related to the precipitation of constituents at the grain boundaries. Thin oxide scales are present on samples furnace heated the longest at the highest temperatures. Acicular structures associated with burning occurred on corresponding samples heated by flame.



(a) Chromium-nickel alloy coating.



(b) Electrodeposited-zinc coating.

Figure 13. - Surface appearance of furnace-heated samples of plain carbon steels coated with metal-sprayed chromium-nickel alloy and plain carbon steels coated with electrodeposited zinc. The chromium-nickel coatings appear to afford protection to the basis metal under all conditions of heating. The full extent of the blistering on the zinc coatings is not shown in these was lost in handling. Compare with figures 19

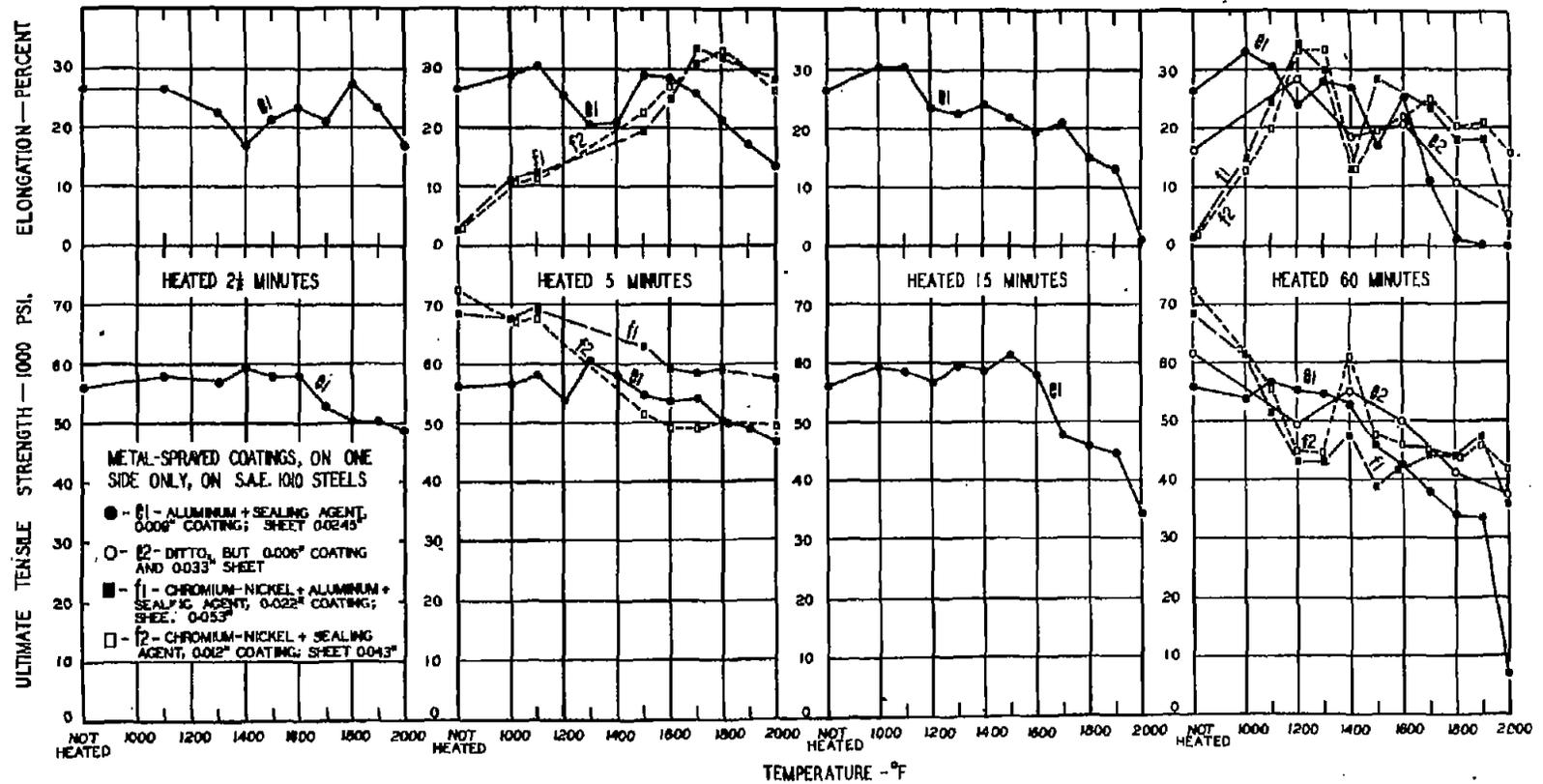
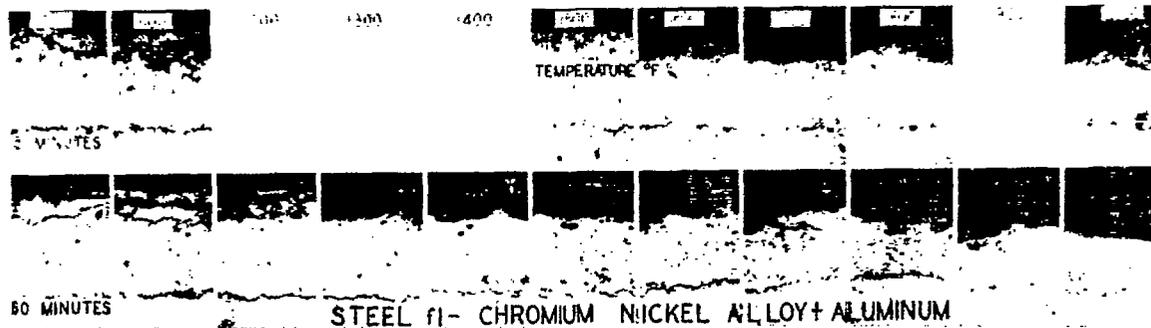
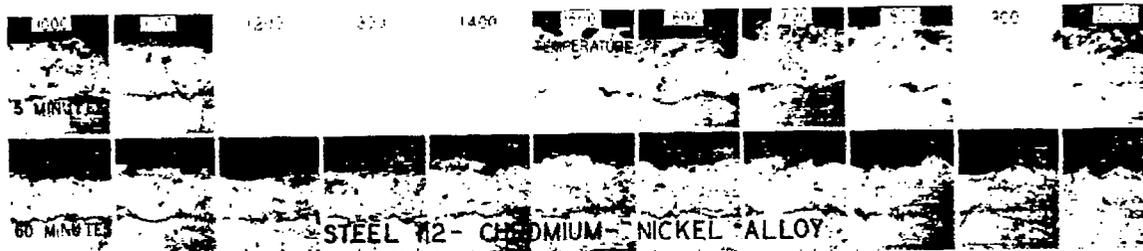


Figure 14. - Changes in tensile properties of furnace-heated samples of plain carbon steels with aluminum or chromium-nickel alloys applied by metal spraying. Serious damage occurred only at the more severe heating conditions owing to the fact that one side of the samples was uncoated.

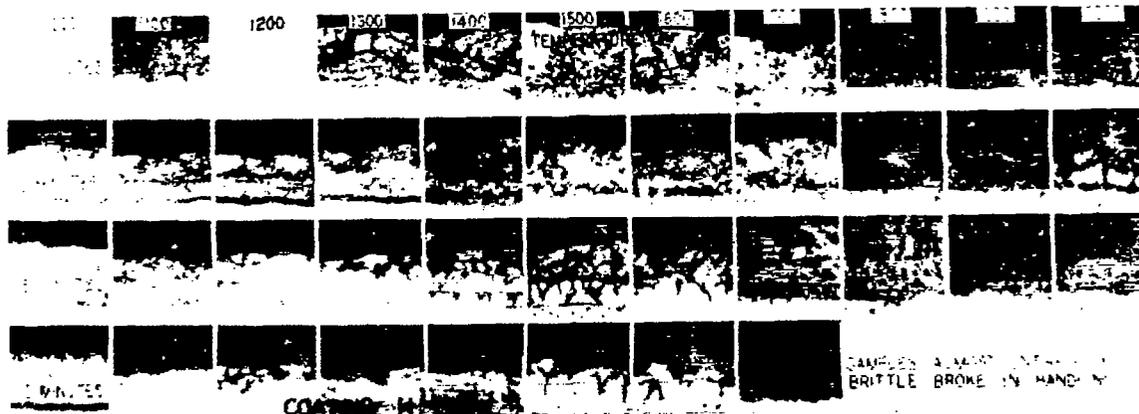
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(a) Chromium-nickel alloy plus aluminum. Originally photographed at X100 and reduced to X25.

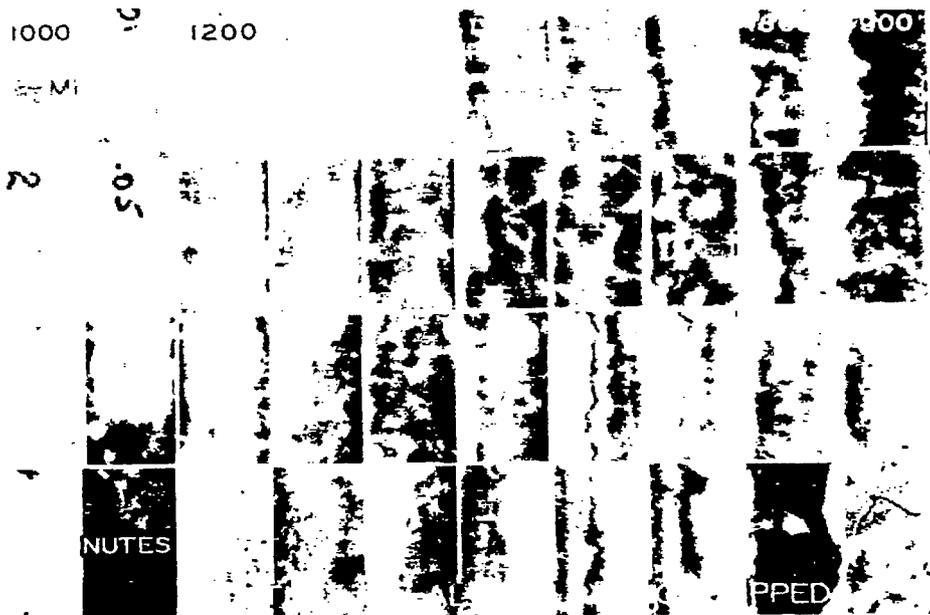


(b) Chromium-nickel alloy. Originally photographed at X100 and reduced to X25.

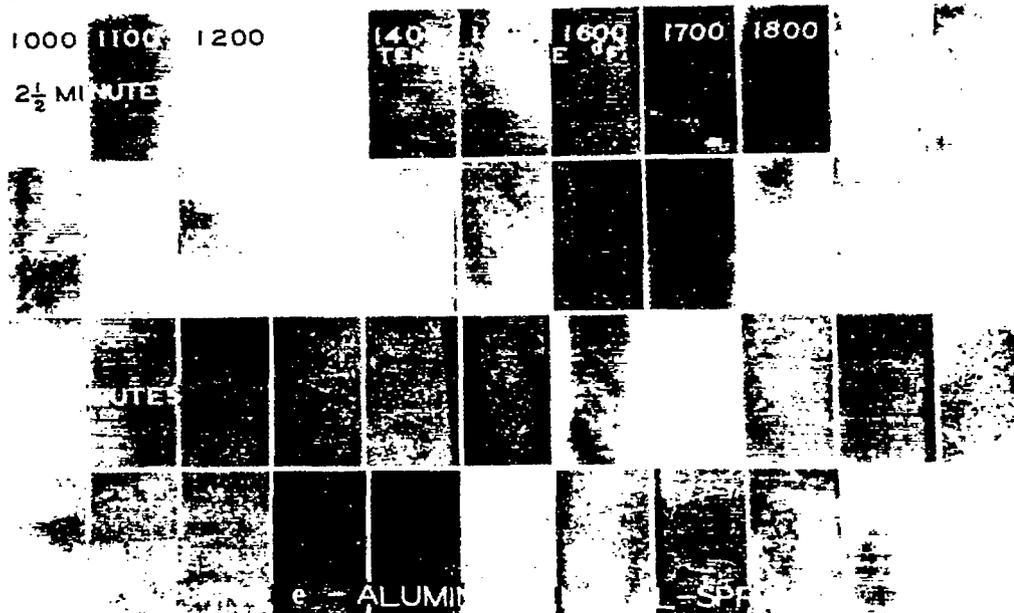


(c) Electrodeposited zinc. Originally photographed at X500 and reduced to X125.

Figure 15. - The microstructures of furnace-heated plain carbon steels coated with metal-sprayed chromium-nickel alloy plus aluminum, chromium-nickel alloy, and electrodeposited zinc. The chromium-nickel coatings although slightly reduced in thickness afforded excellent protection at the most severe heating conditions. The zinc reacted with air to form powdery oxides at the lower temperatures, while the zones alloying with the basis metal became thicker with increases in temperature. Above 1800° F, the surface products were mostly iron oxides.



(a) Hot-dipped aluminum coating.



(b) Metal-sprayed aluminum coating.

Figure 16. - Surface appearance of furnace-heated samples of plain carbon steels coated with hot-dipped and metal-sprayed aluminum. Partial melting can be noted on the hot-dipped coatings but not on the metal-sprayed coatings. The aluminum-iron alloys formed during heating appeared to give ample protection under the most severe heating conditions. Compare with figure 23. X2/3.

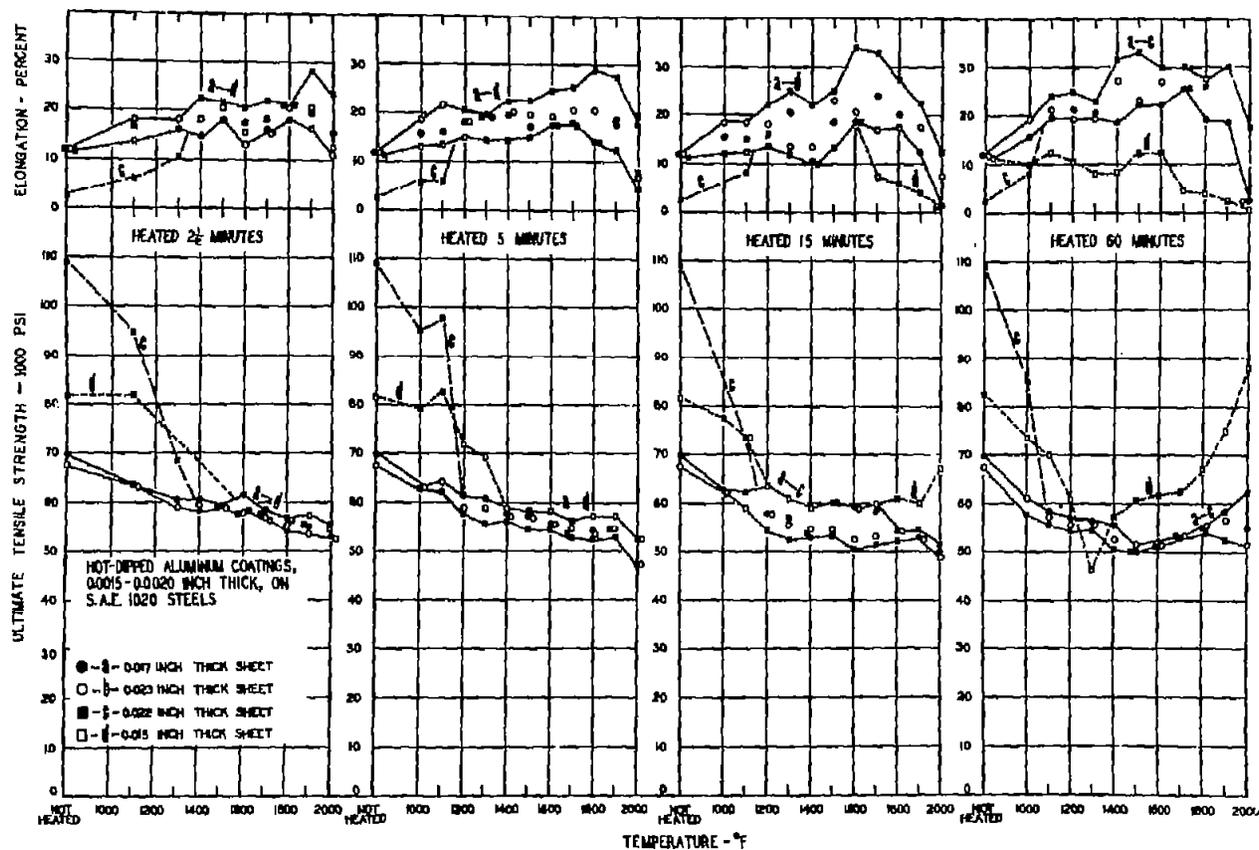
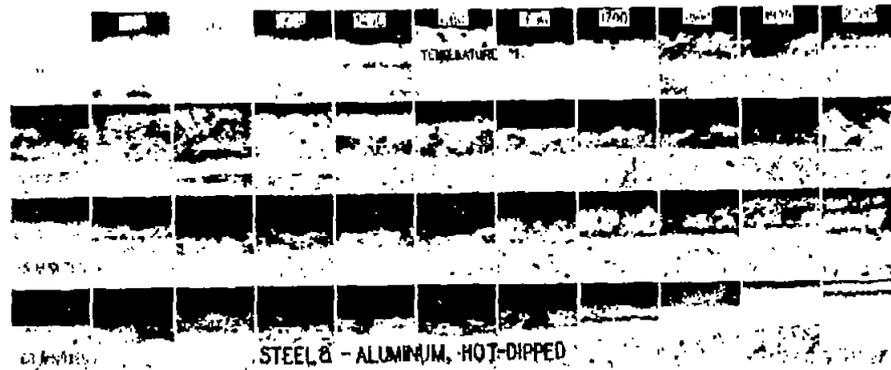
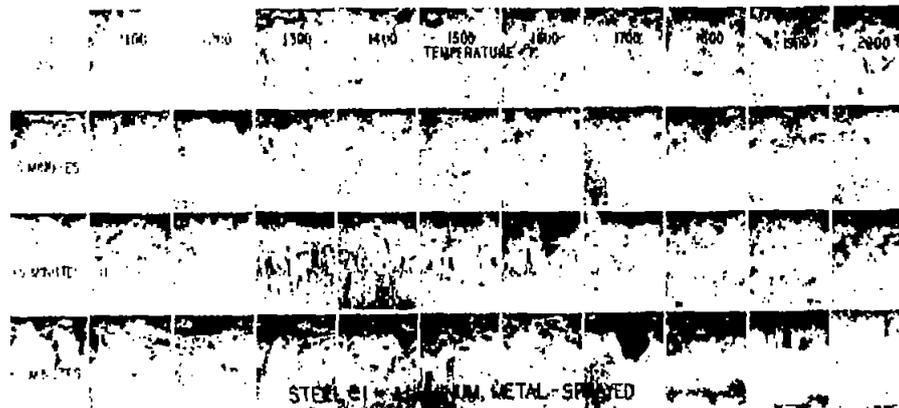


Figure 17. - Changes in tensile properties of furnace-heated samples of plain carbon steels coated with hot-dipped aluminum. Materials of initially higher strength were markedly annealed when heated from 1000° F to 1400° F but thereafter conformed to the others in behavior. The gain in strength shown by certain samples, particularly sheet d, is attributed to the formation of a thick layer of aluminum-iron alloy which ultimately comprised almost the entire cross section. The ordinates of the continuous lines show the range in properties, irrespective of the coating.

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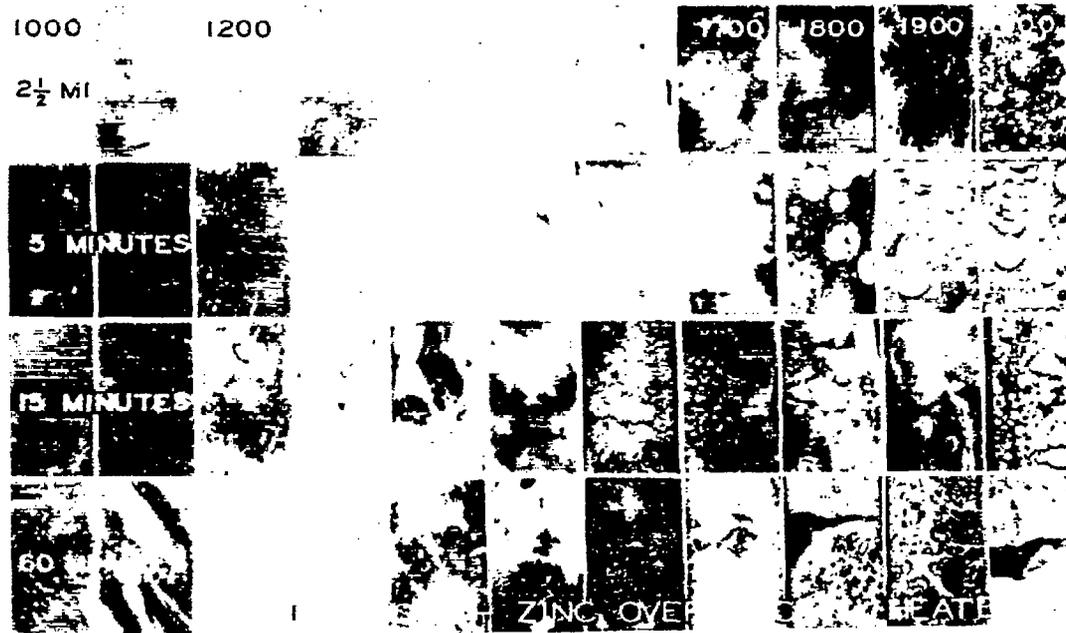
(a) Hot-dipped aluminum coating. Originally photographed at X250 and reduced to X85.



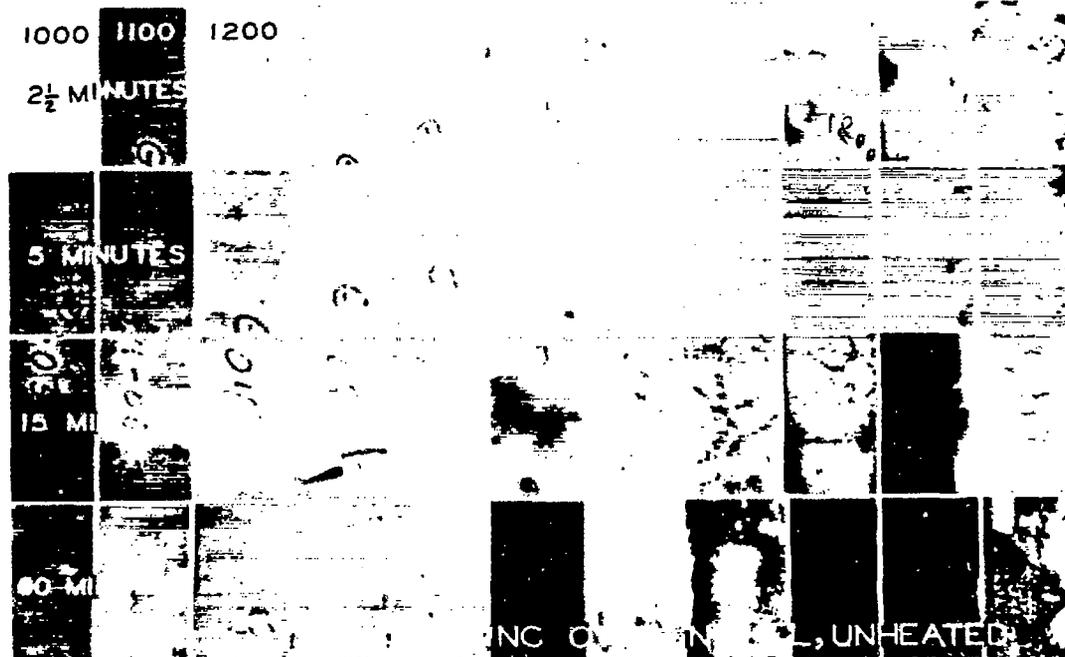
(b) Metal-sprayed aluminum coating. Originally photographed at X250 and reduced to X50.

Figure. 18. The changes in microstructure of furnace-heated plain carbon steels coated with aluminum applied by hot dipping or metal spraying. Progressive alloying of aluminum with the iron resulted with increase of temperature and time. At the more severe heating conditions, the alloys had almost entirely replaced the original basis metal.

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(a) Electrodeposited zinc over nickel, heated.



(b) Electrodeposited zinc over nickel, unheated.

Figure 19. - Surface appearance of furnace-heated samples of plain carbon steels coated with heated and unheated electrodeposited zinc over nickel. The micrographs show the surface appearance of the samples after furnace heating. The unheated samples show a smooth surface, while the heated samples show a porous surface. The porous surface is due to the oxidation of the zinc during handling. Com-

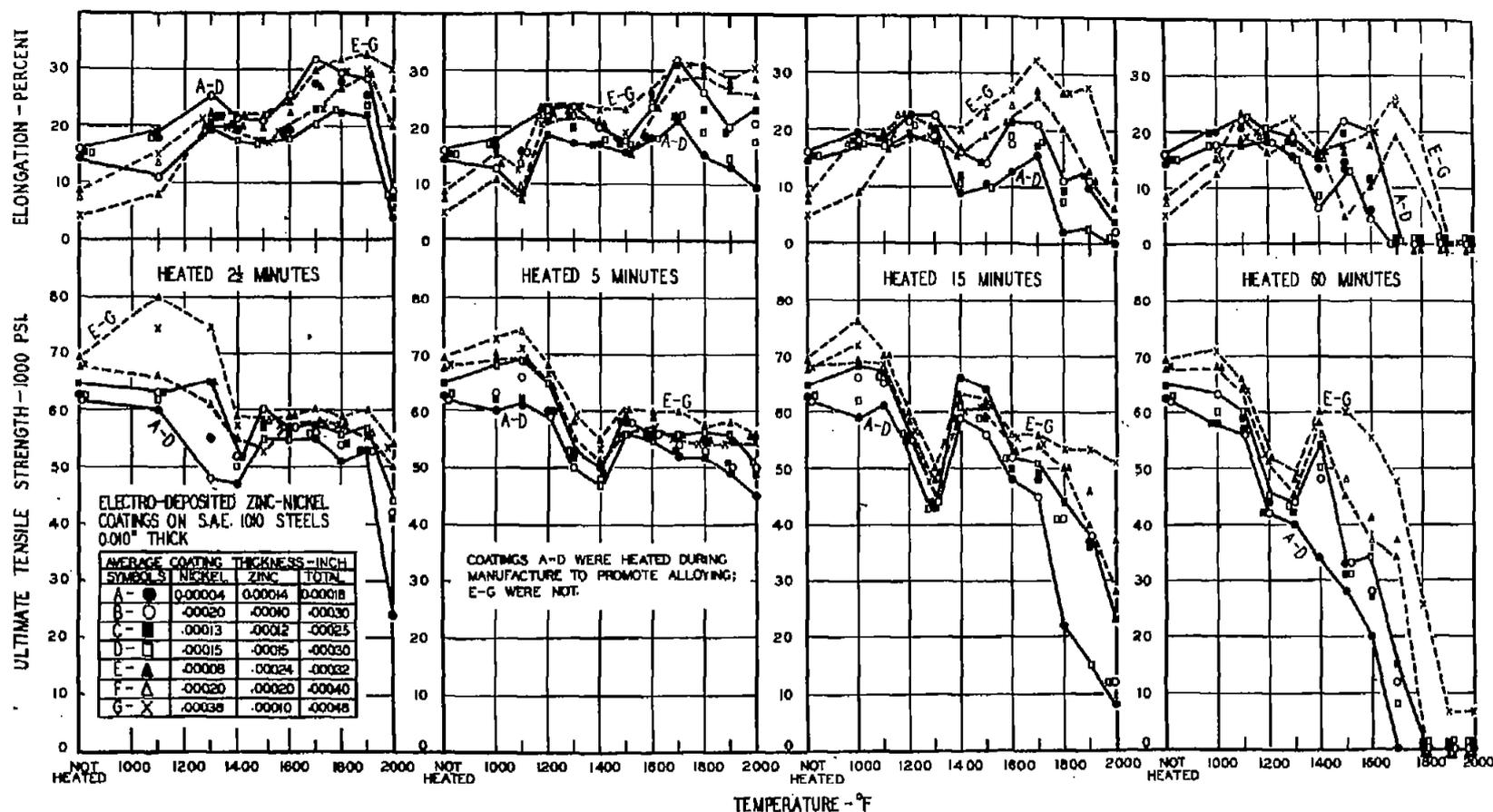
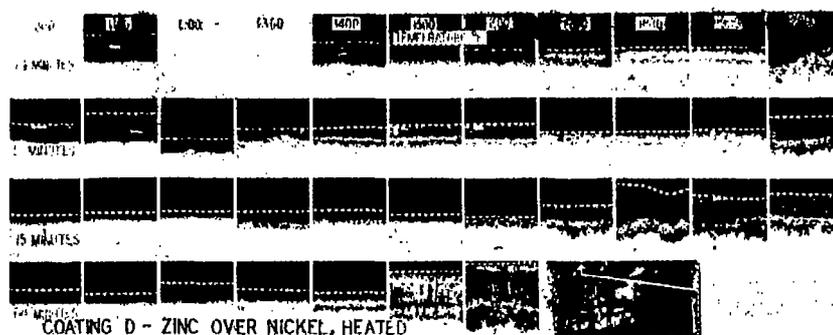
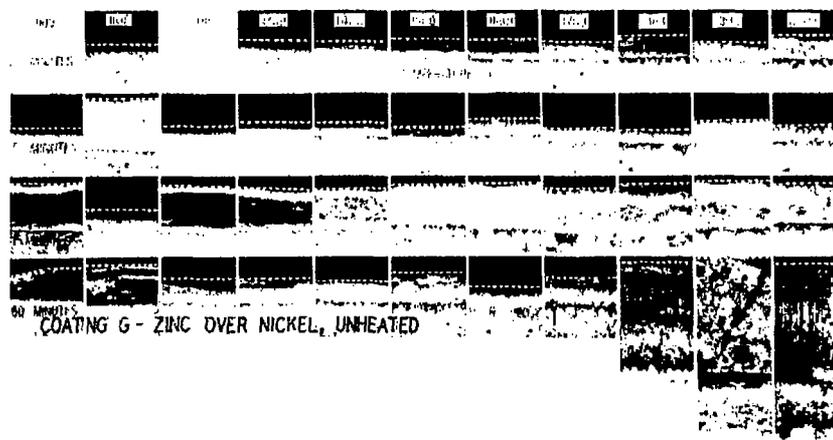


Figure 20. - Changes in tensile properties of furnace-heated samples of plain carbon steels coated with heated and unheated electrodeposits of zinc over nickel. Rates of change were markedly similar for all samples, but sheets E, F, and G showed consistently higher properties. The brittle zinc-iron alloy formed during heating on sheets of this thickness may have contributed to the loss in properties; these losses, however, were usually not of serious magnitude on samples heated as long as 5 minutes.

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(a) Electrodeposited zinc over nickel, heated.



(b) Electrodeposited zinc over nickel, unheated.

Figure 21. - The microstructures of furnace-heated plain carbon steels coated with heated and unheated electrodeposits of zinc over nickel. The dashed white lines indicate the approximate thickness of the loosely adherent powdery zinc oxides most of which were lost during handling. The iron-nickel alloys were probably replaced by oxides rich in iron at the most severe heating conditions. Originally photographed at X500 and reduced to X150.

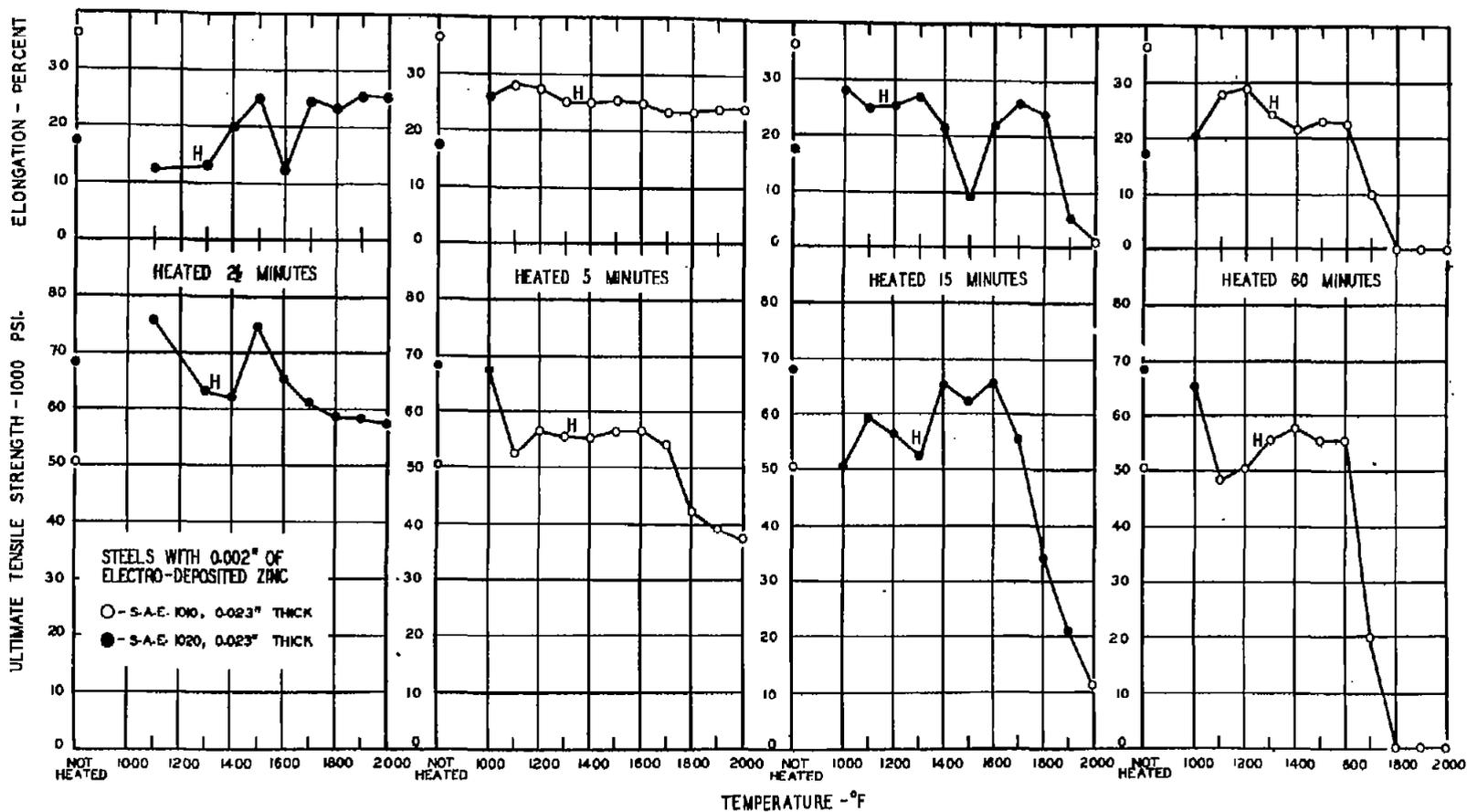


Figure 22. - Changes in tensile properties of furnace-heated plain carbon steels coated with electro-deposited zinc. The steels were taken from at least two lots of different compositions but, in general, the results are in good agreement with those shown in figure 20.

PERIOD, MIN.	TEMPERATURE, °F										
	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000
2 1/2											
5	A				B				C		E
15											
60									D		

2-d - ALUMINUM, HOT-DIPPED

PERIOD, MIN.	TEMPERATURE, °F										
	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000
2 1/2											
5		A			B		C			D	
15											
60											E

A-D - ZINC ON NICKEL, HEATED

PERIOD, MIN.	TEMPERATURE, °F										
	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000
2 1/2											
5			A			B		C		D	
15											
60											E

e - ALUMINUM, SPRAYED

PERIOD, MIN.	TEMPERATURE, °F										
	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000
2 1/2											
5		A			B			C		D	
15											
60											E

E-G - ZINC ON NICKEL, UNHEATED

PERIOD, MIN.	TEMPERATURE, °F										
	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000
2 1/2											
5		A						B			
15											
60										C	

f - CHROMIUM-NICKEL ALLOY

PERIOD, MIN.	TEMPERATURE, °F										
	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000
2 1/2	A										
5					B					F	
15				C			E				
60				D							G

H - ZINC

Figure 23. - Summary of changes in surface appearance after furnace heating of the plain carbon steels with various surface coatings. The changes of the stainless-clad steels coating were practically identical with those of the uncoated stainless-steel samples. (See Fig. 11.) The table facing this page lists the color changes of the surface oxides and physical characteristics of the coatings at different temperatures.

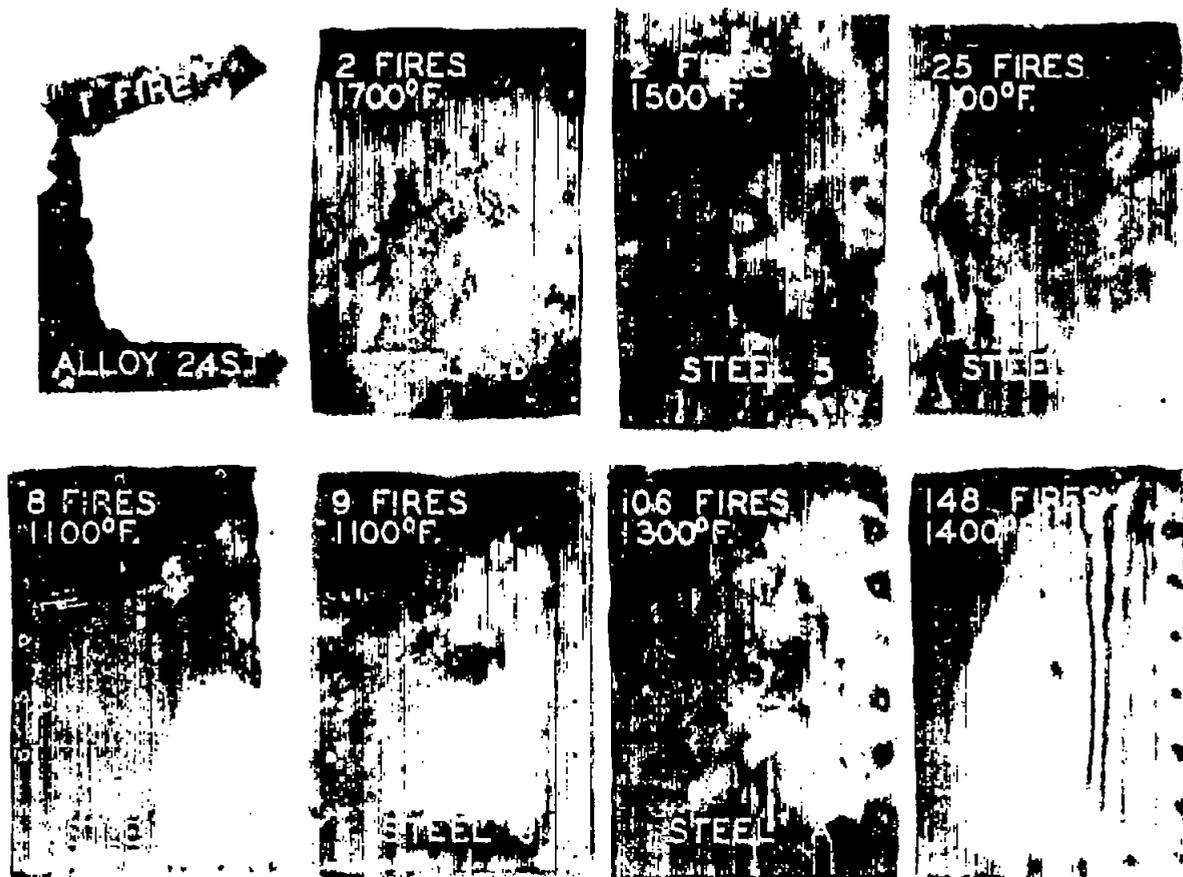


Figure 24. - Surface appearance of representative panels after airplane-fire tests (table 2). The thin carbon steels coated with zinc over nickel exhibited the most pronounced warping, but all the ferrous alloys investigated withstood the fires without burning through. A sample of aluminum alloy (duralumin) 0.030 inch thick was subjected to the same test and burned through completely within 15 seconds. (See alloy 24 ST at upper left.) X1/8.

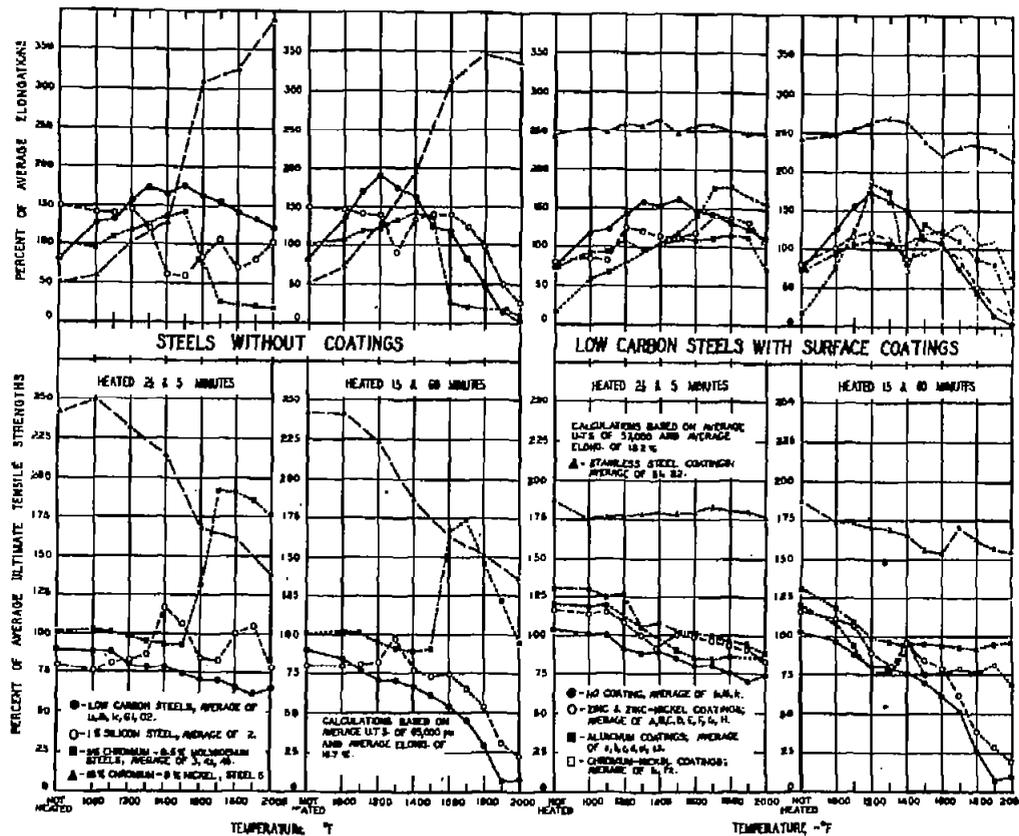


Figure 25. - Summary of changes in tensile properties of all metals investigated. None of the materials appeared to suffer serious damage when heated for periods of 5 minutes or less at the elevated temperatures; the ductility of steels containing 5 percent chromium and 0.5 percent molybdenum, however, was impaired above 1500° F. The stainless-clad steels exhibited the least change under severe heating conditions. The chromium-nickel alloy and the aluminum coatings gave better protection than the zinc coatings.